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**CORE**

DISCUSSION PAPER

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**Auctions with prestige motives**

Olivier BOS <sup>1</sup> and Tom TRUYTS <sup>2</sup>

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**Abstract**

Social status, or prestige, is an important motive for buying art or collectibles and for participation in charity auctions. We study a symmetric private value auction with prestige motives, in which the auction outcome is used by an outside observer to infer the bidders' types. We elicit conditions under which an essentially unique D1 equilibrium bidding function exists in four auction formats: first-price, second-price, all-pay and the English auction. We obtain a strict ranking in terms of expected revenues: the first-price and all-pay auctions are dominating the English auction but are dominated by the second-price auction. Expected revenue equivalence is restored asymptotically for the number of bidders going to infinity.

**Keywords:** costly signaling, D1 criterion, social status, art auctions, charity auctions.

**JEL classification:** D44, D82.

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# 1 Introduction

Humans seem to universally care about social status or prestige.<sup>1</sup> This concern about what others think of them can be either motivated by innate tastes, as humans intrinsically care about others' esteem, or by instrumental reasons, as a higher status often gives access to better mates, partners or resources.<sup>2</sup> Depending on the social and economic context, people seek to establish or suggest their superiority in terms of e.g. income, intelligence, morality, devotion to a common goal or a combination of these. Prestige is also documented to matter in the context of auctions, and in particular for auctions of art and collectibles and for charity auctions.

Mandel (2009) distinguishes three main motives for buying art: investment, direct consumption and conspicuous consumption or signaling. While art serves as a mean of investment much like bonds and stock, owners also derive some private utility from owning art, by enjoying its aesthetic qualities and by the prestige derived from showing it to friends and acquaintances. Mandel (2009) suggests that these consumption and prestige motives explain an old puzzle in the economics of art: why art systematically seems to underperform as an investment compared to bonds and equity, especially when taking the high variance of its yields into account. Mei and Moses (2002) show that the underperformance of art is particularly important for famous masterpieces. This further supports the analysis by Mandel (2009): masterpieces have greater signaling value, such that the willingness to pay for such art further exceeds its investment value. This implies that bidders in an art auction do not only care about the prospects of future profits and the aesthetic qualities of the piece of art, but also about the inferences that other people will make about them in terms of wealth or having sophisticated taste concerning art. These inferences about the individual qualities of a bidder depend on the outcome and form of the auction, and in turn affect the equilibrium bidding strategies and thus the outcome of the auction. The case for prestige motives in the auction of collectibles, such as Elvis Presley paraphernalia, is similar. While the auctioned object undoubtedly also has an important investment and private consumption value, the ownership of such a collectible also reflects in people's inferences about

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<sup>1</sup>See Frank (1985, 1999) for a broad introduction to social status in economics, Miller (2000) for an introduction to the biological roots of status concerns, Mason (1998) for a history of economics thought w.r.t. to status concerns and Truyts (2010) for a recent survey of the literature.

<sup>2</sup>Cole, Mailath and Postlewaite (1992) derive preferences for status from a two-sided one-to-one matching problem. If the equilibrium matching is assortative, one must appear more attractive than one's peers to secure the best attainable partner.

its owner's purchasing power and dedication as a fan.

Charities often raise funds by auctioning objects provided to them by celebrities.<sup>3</sup> In recent years, an extensive literature has analyzed charity auctions as auctions in which bidders' preferences are altruistic.<sup>4</sup> However, the predictions of these theoretical contributions were invalidated in a field experiment (Carpenter et al. 2005). Moreover, the broad theoretical and empirical literature on charity donations suggests that prestige is an important motive for contributions to charity. Glazer and Konrad (1996) and Harbaugh (1998a,b) show that signaling is an important explanation for observed patterns in donations to universities. Kumru and Vesterlund (2010) find that donations are significantly higher if the charity first collects from high status sponsors because donors like to be associated with higher status groups. Moreover, the mechanism of auctioning goods belonging to celebrities seems to exploit prestige motives for charitable fundraising. A unique auctioned object such as Shakira's bra has the same intrinsic qualities as an ordinary bra, but can be shown to friends and acquaintances as a testimony of a winning bid in a charity auction.

We study a symmetric independent private value auction with prestige motives. A single and indivisible commodity is allocated by means of an auction to the one out of  $n$  bidders who submits the highest bid. Each bidder independently draws a private valuation for the auctioned object according to the same distribution and this valuation is her private information. The bidders' payoffs consist of a standard and a prestige component. As in the standard auction model, a winner's *ex post* payoff equals her private valuation for the object minus her payment and a loser's payoff is minus her payment.<sup>5</sup> In addition, we assume that each bidder also cares about the beliefs of an outside party, the receiver, about her type. The receiver is assumed to observe and use the auction outcome, *in casu* the identity and payment of the auction's winner, to form beliefs about the private valuation of all bidders. We study how such a taste for prestige affects the bidding behavior and auction outcome. How does the payment rule affect the inferences by the receiver and thereby the bidding strategies? Does expected revenue equivalence

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<sup>3</sup>E.g. an auction of Blackie, a guitar belonging to Eric Clapton, raised \$959,500 for his alcohol and drug treatment center Crossroads Centre in 2011 (<http://articles.latimes.com/2004/jun/26/entertainment/et-quick26.3>), while a bra of Shakira was auctioned for \$3000 to benefit the Bare Feet Foundation ([http://articles.chicagotribune.com/2008-02-13/news/0802120688\\_1\\_oral-fixation-tour-shakira-hips-don-t-lie](http://articles.chicagotribune.com/2008-02-13/news/0802120688_1_oral-fixation-tour-shakira-hips-don-t-lie)).

<sup>4</sup>See for example Engers and McManus (2007) and Goeree et al. (2005).

<sup>5</sup>Losers might also make a payment as in the all-pay auction.

still apply, or can we strictly rank different auction formats in terms of expected revenues?

Note that, in general, a bidder's private valuation can reflect her wealth, sophisticated taste for art, dedication to an artist in the case of collectibles, generosity in the case of a charity auction, or a combination of all these qualities. We choose to disregard how these qualities map into a private valuation, and how the receiver seeks to reverse this mapping to form beliefs about these qualities from the auction outcome. Such a mapping depends greatly on the particular application one has in mind, and we prefer to keep this implicit to keep the model as simple and generic as possible. Note also that Mandel's (2009) first motivation for buying art or collectibles, investment, reduces to a constant under the assumption of common information for all bidders and can thus be safely disregarded for the present purposes.

Because of the combination of a costly signaling game and an auction into a single game, a general mechanism design approach to this problem seems beyond the current state of the art. For this reason, we analyze the implications of prestige motives in four well known auction formats: the first-price auction, the second-price auction, the all-pay auction and the English auction. Auctions with prestige motives inherit the usual equilibrium multiplicity of signaling games, due to a lack of restrictions on out-of-equilibrium beliefs. Therefore, we restrict out-of-equilibrium beliefs by means of the D1 criterion of Banks and Sobel (1987). The D1 criterion is the most common way of restricting out-of-equilibrium beliefs in signaling games with multiple types, and imposes a monotonicity on out-of-equilibrium beliefs: an out-of-equilibrium bid  $b$  is never attributed to a certain bidder type if a higher type bids in equilibrium less than  $b$ . We show that only fully separating equilibria survive the D1 criterion if the density function characterizing the ex ante distribution of bidders' types is non-increasing. We elicit conditions for the existence of an essentially unique D1 equilibrium bidding function in these four auctions formats, and we show that for a finite number of bidders, the first-price and all-pay auctions outperform the English auction in terms of expected revenues, but are in turn outperformed by the second-price auction. This strict revenue ranking is due to the different amounts of information available to the receiver and the bidders in the different auction formats. Expected revenue equivalence is restored asymptotically for the number of bidders tending to infinity.

To our knowledge, this is the first paper to explore the theoretical implications of prestige motives in an auction setting. However, others have previously analyzed signaling in auctions. The closest to our analysis are

models of information transmission in auctions in function of an after-market. Goeree (2003) studies oligopolists' bidding for a single-license patent on a cost reducing technology. Each oligopolist has private information about the cost reduction which winning the patent would imply for her firm and other oligopolists try to infer the winner's production cost reduction from the auction outcome to determine their strategies in the aftermarket Cournot competition game. However, Goeree's setting and results are, in many respects, different from ours. Unlike Goeree (2003), for instance, we assume that all bidders care about the receiver's inference, irrespective of whether they win the auction or not. We also derive conditions for the common D1 selection criterion to select a fully separating bidding equilibrium. Moreover, Goeree obtains expected revenue equivalence of the first-price, second-price and English auctions because of the particular structure which the aftermarket imposes on the game. In a setting similar to Goeree (2003), Katzman and Rhodes-Kropf (2008) show that the auctioneer's announcement policy of bids can change the auction's revenue and efficiency, while Das Varma (2003) elicits conditions for equilibrium existence for a first-price auction with an aftermarket with linear demand functions and Cournot or Bertrand competition.

A second strain of literature studies signaling to other bidders in dynamic auctions. Avery (1998) shows that bidders may use 'jump bids' in the English auction to signal a high valuation in order to scare away competing bidders, thus decreasing the auction's expected revenue and breaking expected revenue equivalence. Hörner and Sahuguet (2007) compare in a dynamic auction context jump bids and cautious bids as strategic signals about private valuation towards other bidders.

The paper is organized as follows. Section 2 introduces the formal setting and equilibrium concept. Sections 3, 4 and 5 respectively characterize the D1 perfect Bayesian equilibrium of the first-price and all-pay auctions, the second-price auction and the English auction. The expected revenues of these auctions are compared in Section 6. Section 7 concludes. All proofs are collected in Appendix.

## 2 Formal Setting

Consider  $n$  bidders, indexed  $i$ , competing for a single object which is allocated through an auction to the highest bidder. Bidder  $i$ 's valuation for the object (her 'type'), is denoted  $V_i$ , and is assumed i.i.d. and drawn according to a  $C^2$  distribution function  $F$  with support on  $[\underline{v}, \bar{v}] \subset \mathbb{R}_+$ . Let  $f \equiv F'$  denote the density function. Bidder  $i$ 's realization of  $V_i$ , denoted  $v_i$ , is her private information, but the number of bidders and

the distribution  $F$  are common knowledge.

To participate in the auction, a bidder submits a non-negative bid. As all bidders share the same beliefs about the other bidder's valuations, they are assumed to follow a symmetric bidding strategy  $\beta : [\underline{v}, \bar{v}] \rightarrow \mathbb{R}_+$ .<sup>6</sup> Let  $\mathbf{b} = \beta(\mathbf{v})$  denote the vector of bids given a vector of valuations  $\mathbf{v}$ , with  $b_i$  the effective bid of  $i$ -th bidder. An auction mechanism maps a vector of bids  $\mathbf{b}$  to a winner, denoted  $i^*$ , and vector of payments  $\mathbf{p}$ . We assume a fair tie breaking in case of multiple highest bids.<sup>7</sup>

Besides the auction's outcome, bidders also care about the beliefs of an uninformed party, the receiver, about their type. This receiver can represent e.g. the general public or press, business contacts or acquaintances of the bidder or experts related to the object sale. The receiver is assumed to observe the auction's winner and her payment  $(i^*, p_{i^*})$ . The receiver's beliefs, denoted  $\mu$ , are a probability distribution over the type space, such that  $\mu_i(v | (i^*, p_{i^*}))$  is a probability of bidder  $i$  being of valuation type  $v$  given  $(i^*, p_{i^*})$ . Let  $\mu(\mathbf{v} | (i^*, p_{i^*}))$  then be a probability distribution over vectors of valuations  $\mathbf{v}$  given  $(i^*, p_{i^*})$ . The receiver's beliefs are (Bayesian) consistent with a bidding strategy  $\beta$  if

$$\mu(\mathbf{v} | (i^*, p)) = \frac{\Pr(i^*, p_{i^*} | \beta(\mathbf{v})) \prod_i f(v_i)}{\int \Pr(i^*, p_{i^*} | \beta(\mathbf{v}')) \prod_i f(v'_i) d\mathbf{v}'} \quad (1)$$

The utility of bidder  $i$ , given an auction outcome  $(i^*, \mathbf{p})$ , consists of two parts. The first part is standard: the valuation for the object for the winner of the auction, minus the payment (which is nonzero for all bidders in the all-pay auction). The second part is the expected value of the receiver's beliefs about bidder  $i$ 's type given  $(i^*, p_{i^*})$ , denoted  $E(V_i | \mu_i(V_i | i^*, p_{i^*}))$ :

$$u_i(v_i, p_i | \mu_i) = \begin{cases} v_i - p_i + E(V_i | \mu_i(V_i | i^*, p_{i^*})) & \text{for winner } i = i^* \\ -p_i + E(V_i | \mu_i(V_i | i^*, p_{i^*})) & \text{for loser } i \neq i^* \end{cases}$$

This utility function either represents a situation in which bidders care directly about the receiver's beliefs, as humans typically care about the good opinion of others, or is shorthand notation for a game in which the receiver chooses an action given her beliefs about a bidder's type,

<sup>6</sup>We denote the bidding strategy in any auction format by  $\beta$ , and only add an additional superscript to specify the auction format when comparing bidding functions of different auction formats for an expected revenue comparison.

<sup>7</sup>That is, for all  $i \in \{j | b_j = \max \mathbf{b}\}$  we have  $\Pr(i = i^*) = \frac{1}{|\{j | b_j = \max \mathbf{b}\}|}$ .

<sup>8</sup>Note that then  $\mu_i(v | (i^*, p_{i^*})) = \int_{\{\mathbf{v} | v_i = v\}} \mu(\mathbf{v} | (i^*, p_{i^*})) d\mathbf{v}$

while the bidder cares about this choice of the receiver.<sup>9</sup> In the latter case, an explicit analysis of the receiver's problem is easily integrated into the model (within the constraints of the linear payoff structure), but does not add much to our analysis. Although somewhat restrictive, this linear payoff structure seems the most natural benchmark case to study the role of prestige motives in auctions, and ensures that the different auction formats studies below are equivalent in terms of expected revenues in the absence of prestige motives.<sup>10</sup>

We study the symmetric perfect Bayesian equilibria (PBE) of this auction game with prestige motives. A PBE is then described by a pair bidding strategy and beliefs  $(\beta, \mu)$  such that:

1. The bidding function  $\beta$  maximizes expected utility for all  $v$ , given that all other bidders play  $\beta$  and given the receiver's beliefs  $\mu$
2. The receiver's beliefs  $\mu$  are Bayesian consistent with the bidding function  $\beta$ , as in (1).

Because this equilibrium concept imposes no restrictions on out-of-equilibrium beliefs, i.e. how the receiver interprets auction outcomes which should never occur on the equilibrium path, we face the usual equilibrium multiplicity of signaling games. Therefore, we use the D1 criterion of Banks and Sobel (1987), which refines the set of equilibria by restricting out-of-equilibrium beliefs. The D1 criterion restricts out-of-equilibrium beliefs by considering which bidder types are more likely to gain from an out-of-equilibrium bid, compared to their equilibrium expected utility. More precisely, if the set of beliefs for which a bidder gains from a deviation to an out-of equilibrium bid  $b$  (w.r.t. his equilibrium

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<sup>9</sup>At first sight, this utility function may strike some readers as counterintuitive, because it appears as if losing bidders still win something in terms of inference by the receiver. This is only true if one assumes that non-participants receive payoff zero. Rather, our underlying assumption is that the receiver always forms beliefs about the bidders. In this case, a non-participating bidder obtains payoff  $E(V)$ , because the auction reveals no information about her. Since the auction reveals information about both winning and losing bidders, it seems more interesting to take both contingencies into account. In this case, losing bidders lose in equilibrium compared to their non-participation payoff. Note that we argue that our payoff function is intuitive, interesting and consistent, not that it is the only relevant one.

<sup>10</sup>One can also conceive a payoff function

$$\begin{cases} v_i - p_i + \gamma E(V_i | \mu_i(V_i | i^*, p_{i^*})) & \text{for winner } i = i^* \\ -p_i + \gamma E(V_i | \mu_i(V_i | i^*, p_{i^*})) & \text{for loser } i \neq i^*, \end{cases}$$

in which parameter  $\gamma$  a strictly positive and finite real number measuring the relative importance of prestige. However, this would not change our results qualitatively, and would only complicate the analysis.



expected utility) is larger for one bidder type than for another, then the D1 criterion requires out-of-equilibrium beliefs to attribute zero probability the latter type having deviated to  $b$ .<sup>11</sup> The D1 criterion imposes a certain monotonicity on out-of-equilibrium beliefs, which excludes many implausible equilibria, as illustrated below.

### 3 First-price and all-pay auctions

In this Section, we derive the unique D1 perfect Bayesian equilibrium bidding strategies for the first-price auction and all-pay auction. In the first-price auction, the winner pays her own bid. Because the receiver observes the identity of the winner and her payment, she observes the winner's bid. Thus, if  $\beta'(\cdot) > 0$ , the winner's type is fully revealed in equilibrium. The receiver is not able to distinguish among the different losers. The following simple example demonstrates that without imposing the D1 criterion, a multiplicity of equilibria can be supported by often implausible out-of-equilibrium beliefs.

**Example 1 (Zero revenue auction)** *Let  $n = 2$  and  $F$  the uniform distribution on  $[0, 1]$ . Then a PBE exists in which all bidder types bid zero,  $\beta(\cdot) = 0$ , and  $\mu(v|(\cdot, 0)) = 1$  for all  $v$  and  $i$ , while for any  $p_{i^*} > 0$  beliefs about the winner are degenerate at  $v = 0$ , i.e.  $\mu_{i^*}(v'|i^*, p_{i^*}) = 0$  for all  $v' > 0$ . In this case, the expected utility of a  $v$  type in equilibrium is  $\frac{v}{2} + \frac{1}{2}$ , i.e. both winner and loser are inferred by the receiver as  $E(V) = \frac{1}{2}$ , and both bidders win the auction with a probability of  $\frac{1}{2}$ . A bidder deviating to a bid  $\varepsilon > 0$  wins with certainty, pays  $\varepsilon$  and is inferred as a zero valuation type, which implies expected utility  $v - \varepsilon$ , which is strictly below  $\frac{v}{2} + \frac{1}{2}$  for all  $v \in [0, 1]$ . As no bidder makes a strictly positive bid, the illustrated beliefs are consistent with the PBE bidding strategies.*

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<sup>11</sup>As outlined in Appendix, the exact formal implementation of the D1 criterion depends on the auction format. Formally, for types  $v', v''$  and out-of-equilibrium message  $m$ , beliefs  $\mu$ , a utility function  $u(m, \mu|v)$  and equilibrium utility levels  $u^*(v)$ , define the following two sets of beliefs which make a type  $v$  sending  $m$  resp. strictly better off than in equilibrium and equally well off as in equilibrium:

$$\begin{aligned} M^+(m, v) &= \{\mu | u(m, \mu|v) > u^*(v)\} \\ M^0(m, v) &= \{\mu | u(m, \mu|v) = u^*(v)\}. \end{aligned}$$

Then the D1-criterion requires

$$M^+(m, v') \cup M^0(m, v') \subset M^+(m, v'') \implies \mu(v'|m) = 0.$$

Therefore, we restrict out-of-equilibrium beliefs by means of the D1 criterion.<sup>12</sup> Although the D1 criterion typically excludes (semi)pooling PBE in monotonic signaling games at the one hand, and although (semi)pooling strategies are normally easily excluded in auctions with the present preference structure at the other hand, the exercise of excluding (semi)pooling equilibria by means of the D1 criterion is less obvious when both games are combined into an auction with prestige motives. The reason is that bidders cannot be excluded to bid above their valuation for the object (and typically do so in equilibrium). As usual, the D1 criterion ensures that the receiver puts zero probability on all types lower than the maximal type in a pool when observing a bid marginally above the common bid in this pool. In monotonic signaling games this implies that a marginal increase above the pool's signal is rewarded by a discrete jump in terms of inference by the receiver, which immediately excludes (semi)pooling equilibria. In the present setting, however, such a marginal increase in bid also increases a deviating bidder's chances of winning the auction, and thereby her expected payment, by a discrete amount.

To ensure that the D1 criterion has enough bite in the present setting, we restrict  $F$  to be concave, i.e.  $f'(\cdot) \leq 0$ . This condition is (amply) sufficient to exclude potentially complicated (semi)pooling in the D1 PBE, but will also prove close to a necessary condition for the existence of a separating D1 PBE in the second-price auction and English auction. Note that this condition implies the common log-concavity of  $F$  or the non-decreasing hazard rate condition, but is neither stronger nor weaker than the log-concave density condition imposed by Goeree (2003). A similar condition is found in Segev and Sela (forthcoming). This condition implies that only fully separating equilibria survive the

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<sup>12</sup>Note that the equilibrium in example 1 survives the less restrictive Intuitive criterion of Cho and Kreps (1987). The Intuitive criterion requires that no bidder type can gain from deviating to an out-of-equilibrium bid for all possible beliefs that assign zero probability to types who can never gain from such a deviation (w.r.t. their equilibrium payoff), i.e. not for any beliefs by the receiver. In example 1, first, bidders with a valuation strictly lower than  $\hat{v}(b) = 2b - 1$  can never gain from a deviation to out-of-equilibrium bid  $b \in [\frac{1}{2}, 1]$ , and are excluded from the support of out-of-equilibrium beliefs. Second, in this case, no bidder type can gain from a deviation to  $b$  for all remaining out-of-equilibrium beliefs. The worst out-of-equilibrium belief puts all probability mass on type  $\hat{v}(b)$ , such that a deviator gets  $v + 2b - 1 - b$ , which is strictly below the equilibrium payoff  $\frac{v+1}{2}$  for all  $v$ . For  $b < \frac{1}{2}$ , no types can be excluded, such that the worst possible out-of-equilibrium beliefs are better than the equilibrium beliefs (which put all mass on the 0 type). No bidder can ever gain from a deviation to a bid  $b > 1$ . This motivates our use of the more restrictive D1 criterion.

D1 criterion.<sup>13</sup>

**Lemma 1** *If  $f'(\cdot) \leq 0$ , all D1 PBE are fully separating, with  $\beta'(\cdot) > 0$ .*

If the D1 PBE of the first-price auction is fully separating, then the winner's type is fully revealed to receiver, as  $\beta^{-1}(\beta(v_{i*})) = v_{i*}$ . If the winner's type is known to be  $v_{i*}$ , the expectation of a loser's valuation is  $\frac{1}{F(v_{i*})} \int_{\underline{v}}^{v_{i*}} x dF(x)$ . However, if a  $\tilde{v}$  type does not win, she *ex ante* does not know the winner's valuation (except that it is above  $\tilde{v}$ ), such that her expectation of the receiver's inference about a loser is

$$\frac{\int_{\tilde{v}}^{\bar{v}} \frac{1}{F(y)} \int_{\underline{v}}^y x dF(x) dF^{n-1}(y)}{1 - (F^{n-1}(\tilde{v}))}.$$

Moreover, if  $\beta$  is strictly increasing and valuations are drawn independently, the probability of winning for a bidder with a valuation  $v$  is  $F^{n-1}(v)$ . Given an equilibrium bidding function  $\beta$  and corresponding beliefs, we understand a type  $v$  bidder's problem as maximizing her expected utility by choosing which type  $\tilde{v}$  to mimic, by submitting the latter's equilibrium bid  $\beta(\tilde{v})$  to obtain her expected inference by the receiver and probability of winning. As such, the  $v$  type bidder's problem is

$$\max_{\tilde{v}} (F^{n-1}(\tilde{v})) (v - \beta(\tilde{v}) + \tilde{v}) + (1 - (F^{n-1}(\tilde{v}))) \frac{\int_{\tilde{v}}^{\bar{v}} \frac{1}{F(y)} \int_{\underline{v}}^y x dF(x) dF^{n-1}(y)}{(1 - (F^{n-1}(\tilde{v})))}.$$

The first order condition can be written

$$\frac{\partial}{\partial \tilde{v}} (F^{n-1}(\tilde{v}) \beta(\tilde{v})) = (F^{n-1}(\tilde{v}))' (v + \tilde{v}) + (F^{n-1}(\tilde{v})) - \frac{1}{F(\tilde{v})} \int_{\underline{v}}^{\tilde{v}} x dF(x) (F^{n-1}(\tilde{v}))', \quad (2)$$

Of course, in equilibrium  $\beta$  must be such that each bidder strictly prefers her own type's equilibrium bid. Therefore, we impose  $\tilde{v} = v$ , solve the differential equation in (2) and simplify the bidding function. Finally, we verify the second order condition for each  $v$  to ensure that each type maximizes her expected utility by choosing her equilibrium bid  $\beta(v)$ . Let  $E(V_1^{(n-1)} | V \leq v)$  denote the expected value of the highest order statistic out of  $n-1$  draws, for a distribution truncated at the right at  $v$ , and let  $E(V | V \leq v)$  denote the expected value of a single

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<sup>13</sup>Note that we use 'fully separating' to indicate that no bid is chosen by different types in equilibrium. In the present setting, this does not imply that the receiver's equilibrium beliefs are degenerate, which is sometimes used as an alternative definition of 'fully separating' equilibrium.

draw, for  $F$  truncated at the right at  $v$ . The essentially unique D1 PBE bidding function for the first-price auction is then characterized in the following Proposition.

**Proposition 1** *For  $n \geq 3$  and  $f'(\cdot) \leq 0$ , the essentially unique first-price auction D1 PBE bidding strategy is*

$$\beta(v) = v + \frac{n-1}{n-2} \left( E \left( V_1^{(n-1)} | V \leq v \right) - E(V | V \leq v) \right) \quad (3)$$

with  $\lim_{v \rightarrow \underline{v}^+} \beta(v) = \underline{v}$ ,  $\beta(\bar{v}) = \bar{v} + \frac{n-1}{n-2} \left( E \left( V_1^{(n-1)} \right) - E(V) \right)$  and finally  $\beta'(\cdot) > 1$ .

Remark that for arbitrary  $F$  there is no fully separating equilibrium in the first-price auction with two bidders. The equilibrium bidding strategy in (3) is only essentially unique because the equilibrium bid of the  $\underline{v}$  valuation type is undetermined: because she has zero probability of winning the auction in equilibrium, any bid in the interval  $[0, \underline{v}]$  is payoff equivalent. In the limit, however, the lowest valuation types bid  $\underline{v}$ . In terms of inference by the receiver, the lowest valuation types have little to gain from winning. Winning reveals them as lowest types, while they are better off in terms of inference by losing against a higher type. Yet, if an interval of lowest valuation types would bid weakly below  $\underline{v}$  (while respecting  $\beta'(\cdot) > 0$ ), then the  $\underline{v}$  type can profitably deviate to a bid  $\underline{v}$  to win with non-zero probability, pay  $\underline{v}$  for an object valued  $\underline{v}$  and be inferred by the receiver to have a valuation strictly above  $\underline{v}$ . As suggested above, all bidders with a valuation strictly higher than  $\underline{v}$  bid above their valuation of the object. The difference between a bidder's valuation for the object and her equilibrium bid strictly increases with the bidder's valuation. For  $n \rightarrow +\infty$ , the highest valuation types bid  $\beta(\bar{v}) = 2\bar{v} - E(V)$ , which equals their valuation for the object plus the difference in the receiver's inference about them if winning ( $\bar{v}$ ) rather than losing ( $E(V)$ ) the auction.

**Example 2 (Uniform on  $[0, 1]$ )** *In this case, the bidders' problem is*

$$\max_{\tilde{v}} (v - \beta(\tilde{v}) + \tilde{v}) \tilde{v}^{n-1} + (1 - \tilde{v}^{n-1}) \frac{n-1}{2n} \frac{1 - \tilde{v}^n}{1 - \tilde{v}^{n-1}}.$$

*The D1 PBE bidding function is*

$$\beta(v) = \frac{3n-1}{2n} v.$$

We now proceed to the all-pay auction. Contrary to the first-price auction, all the losers pay their own bid in the all-pay auction. As before, the receiver observes only the identity and payment of the winner. The all-pay auction suffers from the same equilibrium multiplicity due to out-of-equilibrium beliefs as the first-price auction, and imposing the D1-criterion excludes all (semi)pooling equilibria if  $f$  is non-increasing. The proof is technically identical to that of the first-price auction (Lemma 1). As such, the winner's type is fully revealed to the receiver, and the latter's expected inference is equivalent in the first-price and the all-pay auction. In the absence of prestige motives, the expected payoff in the all-pay auction equals the expected payoff in the first-price auction minus  $(1 - F^{n-1}(\tilde{v}))(\beta(\tilde{v}))$  (such that bidders pay their bid with probability 1 instead of  $F^{n-1}(\tilde{v})$ ).

In the absence of prestige motives, both these auctions are revenue equivalent. The addition of an identical term to the expected payoffs of both auction formats, i.e. the expected inference of the receiver, affects the equilibrium bidding functions and the expected payments in the same way in both auctions. As a result, the equilibrium bidding function of the all-pay auction can be obtained by an adaptation of the usual proof of the revenue equivalence theorem (see e.g. Krishna (2009)).

**Proposition 2** *If  $f'(\cdot) \leq 0$  and  $n \geq 3$ , then the unique all-pay auction D1 PBE bidding function is*

$$\beta(v) = F^{n-1}(v)\beta^I(v),$$

*with  $\beta^I(\cdot)$  the first-price auction D1 PBE bidding function,  $\lim_{v \rightarrow \bar{v}^+} \beta(v) = 0$  and  $\beta(\bar{v}) = \beta^I(\bar{v})$ .*

As for the first-price auction, no D1 PBE exists in general for two bidders.

## 4 Second-price auction

In the second-price sealed-bid auction, the winner pays the second highest bid. Because the receiver only observes the identity and payment of the winner, the latter only allows her to bound the set of possible bids of the winner from below and the set of possible bids of the losers from above. This difference in information available to the receiver considerably alters the bidders' expected payoff and equilibrium bidding.

The second-price auction also suffers from a multiplicity of equilibria due to insufficient restrictions on out-of-equilibrium beliefs, which is equally remedied by imposing the D1 criterion. However, the role of

out-of-equilibrium beliefs slightly differs between the first- and second-price auctions. A bidder deviating unilaterally to a bid above the highest equilibrium bid always wins the auction. But such a deviation will not be revealed, because the winner only pays the second highest bid, which has an equilibrium interpretation. Therefore, bids cannot be constrained from above by possibly implausible out-of-equilibrium beliefs in the second-price auction, and a zero revenue auction as in Example 1 is impossible for the second-price auction. Out-of-equilibrium beliefs for bids below the minimal equilibrium bid affect bidding in neither the first- nor the second-price auction because such deviations are never observed, such that implausible out-of-equilibrium beliefs can never constrain equilibrium bidding from below. However, discontinuities in the bidding function at intermediate valuations can be supported by particular out-of-equilibrium beliefs. Such deviations are revealed to the receiver if they constitute the second highest bid, in which case they fix the inference about all losing bidders, including the deviator. Similar to Lemma 1, the following Lemma demonstrates that any D1 PBE bidding function is strictly increasing for non-increasing density functions.

**Lemma 2** *If  $f'(\cdot) \leq 0$  and  $n \geq 3$ , then  $\beta'(\cdot) > 0$  in any D1 PBE of the second-price auction.*

We now proceed step by step to construct the problem of a  $v$  type bidder choosing which type  $\tilde{v}$  to mimic in the second-price auction. As before, a strictly increasing bidding function implies that a type  $v$  bidder choosing the  $\tilde{v}$  type's equilibrium bid wins with probability  $F^{n-1}(\tilde{v})$ . In this case, her payoff is:

$$v + \frac{1}{F^{n-1}(\tilde{v})} \int_{\underline{v}}^{\tilde{v}} \beta(x) dF^{n-1}(x) + \frac{1}{F^{n-1}(\tilde{v})} \int_{\underline{v}}^{\tilde{v}} \frac{\int_x^{\tilde{v}} y dF(y)}{1 - F(x)} dF^{n-1}(x).$$

The second term is the expected payment if  $\beta(\tilde{v})$  is the winning bid and the third term is the receiver's expected inference about a winner of valuation  $\tilde{v}$ . If the second highest bidder is of type  $x$ , then the inference about the winner is  $\frac{\int_x^{\tilde{v}} y dF(y)}{1 - F(x)}$ . But because the second highest bid is unknown to the bidder, the third term takes the expectation over the second highest bid.

Second, with probability  $(n-1)F^{n-2}(\tilde{v})(1 - F(\tilde{v}))$  bid  $\beta(\tilde{v})$  is the second highest bid. In this case, the receiver's inference about any losing bidder is

$$\frac{\tilde{v}}{n-1} + \frac{n-2}{n-1} \frac{\int_{\underline{v}}^{\tilde{v}} x dF(x)}{F(\tilde{v})},$$

as one of the  $n - 1$  losers has valuation  $\tilde{v}$  while the  $n - 2$  others' valuations are weakly lower than  $\tilde{v}$ . Finally, with probability  $1 - F^{n-1}(\tilde{v}) - (n - 1) F^{n-2}(\tilde{v})(1 - F(\tilde{v}))$ , a type  $\tilde{v}$  bidder is neither the highest nor second highest bidder. For this case, a bidder forms an expectation over the second highest bid to assess the receiver's expected inference about the losing bidders.

The expected utility of a valuation  $v$  bidder choosing type  $\tilde{v}$ 's bidding strategy is then:

$$\begin{aligned} & \int_{\underline{v}}^{\tilde{v}} (v - \beta(x)) dF^{n-1}(x) + \int_{\underline{v}}^{\tilde{v}} \frac{\int_{\underline{v}}^{\tilde{v}} y dF(y)}{1 - F(x)} dF^{n-1}(x) \\ & + (n - 1) F^{n-2}(\tilde{v})(1 - F(\tilde{v})) \left( \frac{\tilde{v}}{n - 1} + \frac{n - 2}{n - 1} \frac{\int_{\underline{v}}^{\tilde{v}} x dF(x)}{F(\tilde{v})} \right) \\ & + \int_{\tilde{v}}^{\bar{v}} \left( \frac{y}{n - 1} + \frac{n - 2}{n - 1} \frac{\int_{\underline{v}}^y x dF(x)}{F(y)} \right) d((n - 1) F^{n-2}(y) - (n - 2) F^{n-1}(y)). \end{aligned}$$

The first order condition is

$$\begin{aligned} & \beta(\tilde{v})(F^{n-1}(\tilde{v}))' = v(F^{n-1}(\tilde{v}))' + \frac{\int_{\underline{v}}^{\tilde{v}} x dF(x)}{1 - F(\tilde{v})} (F^{n-1}(\tilde{v}))' \\ & + F^{n-2}(\tilde{v})(1 - F(\tilde{v})) \left( 1 + (n - 2) \frac{\tilde{v} f(\tilde{v}) F(\tilde{v}) - f(\tilde{v}) \int_{\underline{v}}^{\tilde{v}} x dF(x)}{F^2(\tilde{v})} \right) \\ & + ((n - 2) f(\tilde{v}) F^{n-3}(\tilde{v}) - (n - 1) f(\tilde{v}) F^{n-2}(\tilde{v})) \left( \tilde{v} + (n - 2) \frac{\int_{\underline{v}}^{\tilde{v}} x dF(x)}{F(\tilde{v})} \right) \\ & - ((n - 2) f(\tilde{v}) F^{n-3}(\tilde{v}) - (n - 2) f(\tilde{v}) F^{n-2}(\tilde{v})) \left( \tilde{v} + (n - 2) \frac{\int_{\underline{v}}^{\tilde{v}} x dF(x)}{F(\tilde{v})} \right). \end{aligned}$$

After dividing both sides by  $(F^{n-1}(\tilde{v}))' = (n - 1) F^{n-2}(\tilde{v}) f(\tilde{v})$ , imposing  $\tilde{v} = v$  and simplifying, we obtain

$$\begin{aligned} \beta(v) = & v + \frac{\int_{\underline{v}}^v x dF(x)}{1 - F(v)} + \frac{1 - F(v)}{f(v)(n - 1)} \left( 1 + \frac{n - 2}{F(v)} \left( v - \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right) \right) \\ & - \frac{1}{n - 1} \left( v + (n - 2) \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right). \end{aligned} \quad (4)$$

The essentially unique D1 PBE bidding function for the second-price auction is then characterized by the following Proposition.

**Proposition 3** *If either  $n \geq 4$  and  $f'(\cdot) \leq 0$  or  $n = 3$  and  $f'(\cdot) < 0$ , then the essentially unique second-price auction D1 PBE bidding strategy is*

$$\beta(v) = \frac{n-2}{n-1} \frac{v - E(V|V \leq v)}{F(v)} + E(V|V \geq v) + \frac{1 - F(v)}{(n-1)f(v)},$$

*with  $\lim_{v \rightarrow \underline{v}} \beta(v) = E(V) + \frac{n}{n-1} \frac{1}{2f(\underline{v})}$  and  $\lim_{v \rightarrow \bar{v}} \beta(v) = \bar{v} + \frac{n-2}{n-1} (\bar{v} - E(V))$ .*

For the second-price auction, the qualification ‘essential’ reflects that the equilibrium bidding function is undetermined at both extremes of the typespace. If  $\beta'(\cdot) > 0$ , then a  $\underline{v}$  type has the highest or second-highest bid with zero probability, such all bids in  $\left[0, E(V) + \frac{n}{n-1} \frac{1}{2f(\underline{v})}\right]$  are in equilibrium payoff equivalent. At the other hand, for finite  $n$  a  $\bar{v}$  type wins with probability 1 and does not pay her own bid, such that all bids weakly above  $\lim_{v \rightarrow \bar{v}} \beta(v)$  are in equilibrium payoff equivalent. However, the D1 equilibrium bidding function is uniquely determined on  $(\underline{v}, \bar{v})$ . The limit of the equilibrium bidding function at  $\underline{v}$  lies strictly above the average valuation for the object, and thus well above the equilibrium bid in the first-price auction. The reason is that if a very low valuation type wins the auction, the winner is inferred as slightly higher than a  $E(V)$  type by the receiver, while all losers are inferred almost as  $\underline{v}$  types, because the second highest bidder’s type is below the winner’s valuation. Therefore, the lowest types bid at least their valuation  $\underline{v}$  plus the difference in inference by the receiver  $E(V) - \underline{v}$  in equilibrium. A further comparison with the equilibrium bidding function of the English auction in the next Section will provide more intuition for the second-price D1 PBE bidding function.

Note that in the second-price auction, there is also no fully separating equilibrium with two bidders, and even not with three bidders if the density  $f$  is constant over some interval of the support. In the following example with a uniform distribution on  $[0, 1]$ , we comment on this non-existence of an equilibrium with two or three bidders.

**Example 3 (Uniform on  $[0, 1]$ )** *For  $F$  uniform on  $[0, 1]$ , the expected payoff of a  $v$  type bidder imitating a  $\tilde{v}$  type is*

$$\begin{aligned} & \tilde{v}^{n-1} \left( v_i + \frac{1 + \frac{n-1}{n} \tilde{v}}{2} \right) - (n-1) \int_0^{\tilde{v}} x^{n-2} \beta(x) dx \\ & + (n-1) \tilde{v}^{n-2} (1 - \tilde{v}) \left( \frac{n-2}{n-1} \frac{\tilde{v}}{2} + \frac{\tilde{v}}{n-1} \right) \\ & + (1 - \tilde{v}^{n-1} - (n-1) \tilde{v}^{n-2} (1 - \tilde{v})) \frac{\int_{\tilde{v}}^1 \left( \frac{x}{n-1} + \frac{n-2}{n-1} \frac{x}{2} \right) d((n-1)x^{n-2} - (n-2)x^{n-1})}{(1 - \tilde{v}^{n-1} - (n-1) \tilde{v}^{n-2} (1 - \tilde{v}))}. \end{aligned}$$



The D1 PBE bidding function is

$$\beta(v) = \frac{2n - 1 + (n - 3)v}{2(n - 1)}.$$

If  $n = 2$ , a losing bidder is always identified by her true valuation  $v$ , while winners are identified only as the average between the valuation of the loser (in expectation half of her own valuation) and the maximum valuation 1, i.e. the expected inference for  $n = 2$  is

$$\tilde{v} \left( \frac{1}{2} + \frac{\tilde{v}}{4} \right) + (1 - \tilde{v}) \tilde{v} = \frac{3}{4} \tilde{v} (2 - \tilde{v}).$$

For two bidders, the receiver's inference increases more with  $\tilde{v}$  if a bidder loses, but the probability of losing decreases with  $\tilde{v}$ , such that the marginal effect of  $\tilde{v}$  on the receiver's expected inference, i.e.  $\frac{3}{2}(1 - \tilde{v})$ , decreases with  $\tilde{v}$  at a constant rate  $\frac{3}{2}$ . This decrease more than offsets the higher valuation types' incentives to bid strictly more than lower types, which inhibits the existence of a D1 PBE. At  $n = 3$ , both these effects cancel out exactly. Thus, for  $n \leq 3$ , we have no D.1. equilibrium bidding function.

A similar logic applies if  $f$  is constant over an interval in the support of a more general distribution function, such that Proposition 3 requires either that  $n \geq 4$  and  $f'(\cdot) \leq 0$  or that  $n = 3$  and  $f'(\cdot) < 0$ .

## 5 English auction

An important reason for the popularity of the second-price auction among auction theorists is its common strategic equivalence with the English auction, which is more frequently used in reality. However, this equivalence ceases to exist in the presence of prestige motives. This result can be surprising, because the introduction of other externalities, such as financial externalities in charity auctions (e.g. Engers and McManus (2007)), did not break up the strategic equivalence.

The English auction can be studied in various formalizations. We consider a minimal information “button auction” (see e.g. Milgrom (2004)) in which the auctioneer lets the price continuously increase on a price clock. Each bidder chooses when to exit the auction by releasing a button, and such exit is irrevocable. The last bidder holding her button wins, and fixes the price by releasing her button. Bidders only observe whether two or more bidders are still pushing their button or not, and the latter implies that the auction has a winner. This minimal information setting remains closest to the second-price auction, as bidders can learn little about the other bidders' valuations during the auction. We

maintain the assumption that the receiver only observes the identity and the payment of the winner.<sup>14</sup>

In this auction, each bidder has to decide on each moment (or price) whether to stay in or to exit. Note then that in equilibrium, the exit price is increasing with  $v$  because the prospects in terms of inference by the receiver at a certain price are identical for different types, while the lower type values winning the auction strictly less. Again, we restrict out-of-equilibrium beliefs by means of the D1 criterion to avoid the multiplicity of equilibria, and establish that any D1 PBE is fully separating.

**Lemma 3** *In any D1 PBE, the exit rule  $\beta$  is a continuous and strictly increasing function of  $v$ .*

In the usual English auction, the winner drops out immediately after the second last bidder's exit. An inspection of the payoff function shows that once a bidder has won the auction, our setting does not provide her with means to credibly reveal a higher valuation to the receiver (contrary e.g. to Goeree (2003)). In the present setting, the winner's problem would be to choose an exit price  $b_{i^*}$  to maximize  $v_{i^*} - b_{i^*} + E(V|\mu_{i^*}(V|i^*, b_{i^*}))$ . The lack of single crossing property, due to the additive structure of the payoff function, implies that if the receiver would interpret a higher bid in such way that the winner prefers to bid strictly above the second highest bid, then all types of winners would strictly prefer to do so. Therefore, if the penultimate quitter has valuation  $v'$ , then the receiver must have an expectation  $E(V|V \geq v')$  of the winner's valuation for any payment above  $\beta(v')$ , and the winner must exit immediately at  $\beta(v')$ .

If the bidding strategy (i.e. exit price) is strictly increasing with type and if the winner exits at the second highest bid, then the second highest bidder fixes the payoff of all bidders. Since bidders do not observe previous exits by lower valuation bidder's, the latter's strategy does not affect equilibrium bidding. Of course, a bidder does not know whether she has the second highest valuation, but she optimizes her strategy as if this were the case. A type  $v$  bidder then leaves the auction when the

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<sup>14</sup>Obviously other information regimes, e.g. the receiver observing all bids, are equally plausible in this setting. The plausibility of these different scenarios depends on the specific context and the identity of the receiver (e.g. another bidder or the general public reading media outlets). We prefer the present assumption because it keeps the kind of information the receiver disposes of constant throughout the different auction formats.

price hits the bid of a  $\tilde{v}$  type, such that

$$v - \beta(\tilde{v}) + \frac{1}{1 - F(\tilde{v})} \int_{\tilde{v}}^{\bar{v}} x dF(x) = \frac{\tilde{v}}{n-1} + \frac{n-2}{n-1} \frac{\int_{\tilde{v}}^{\bar{v}} x dF(x)}{F(\tilde{v})}. \quad (5)$$

The left hand side of (5) is the payoff a type  $v$  bidder gets if she wins at price  $\beta(\tilde{v})$ , while the right hand side is a loser's payoff, if she releases the button at price  $\beta(\tilde{v})$  with only two bidders left. This exit rule defines a unique equilibrium bidding function of the second highest valuation type, which determines the auction price. This is equivalent to having at each price  $b$  type  $\beta^{-1}(b)$  leaving the auction, such that the optimal exit price of type  $v$  satisfies

$$v - b + \frac{1}{1 - F(\beta^{-1}(b))} \int_{\beta^{-1}(b)}^{\bar{v}} x dF(x) = \frac{\beta^{-1}(b)}{n-1} + \frac{n-2}{n-1} \frac{\int_{\beta^{-1}(b)}^{\bar{v}} x dF(x)}{F(\beta^{-1}(b))} \quad (6)$$

Note in (6) that the receiver's inference about the winner and about all losers increases with  $b$  (or  $\tilde{v}$ ). However, the following proposition establishes that in equilibrium the costs of mimicking a higher type in terms of payment increase faster than the benefits in terms of inference, such that this equality establishes the essentially unique D1 equilibrium exit rule for the English auction.

**Proposition 4** *If  $n \geq 3$  and  $f'(\cdot) \leq 0$ , then the essentially unique D1 PBE exit rule in the English auction is*

$$\beta(v) = \frac{n-2}{n-1} \left( v - \frac{\int_v^{\bar{v}} x dF(x)}{F(v)} \right) + \frac{\int_v^{\bar{v}} x dF(x)}{1 - F(v)}, \quad (7)$$

with  $\lim_{v \rightarrow v^+} \beta(v) = E(V)$  and  $\lim_{v \rightarrow \bar{v}} \beta(v) = \bar{v} + \frac{n-2}{n-1} (\bar{v} - E(V))$ .

Given the optimal exit strategy of a winner in the English auction, the second-price and English auctions are equivalent in terms of information for the receiver. A closer comparison of equilibrium bidding in both auctions can therefore also further clarify the equilibrium in the second-price auction. When comparing the equilibrium bidding functions of the second-price and English auctions, we note both are identical up to the two following additional terms in the former:

$$\frac{1 - F(v)}{F(v)} \frac{n-2}{n-1} \left( v - \frac{\int_v^{\bar{v}} x dF(x)}{F(v)} \right) + \frac{(1 - F(v))}{(n-1)f(v)} > 0,$$

which vanish for  $v \rightarrow \bar{v}$ . A closer inspection of (4) shows that these two additional terms, the third right hand side term in (4), reflect the effect on the receiver's expected inference about all the losing bidders of a marginal increased bid for a given probability of being the second highest bidder.

The main difference between the second-price and English auctions is that in the latter, the set of possible second highest bids is bounded from below by the increasing price clock. If the English auction has no winner at price  $b$ , then all active bidders can take it as a given that the second highest bid is at least  $b$ , and that the receiver's expected inference about the winner will be bounded from below by  $\beta^{-1}(b)$ . This lower bound on the second highest bid also bounds the receiver's expected inference about the losers from below. Therefore, each bidder just compares her payoff as a winner and as a loser with the second higher bid and quits if both are equal. If she turns out not being the second highest bidder, then the payoff of losing certainly exceeds her payoff of winning. As such, (7) means that an active bidder exits when the price equals her valuation plus the difference between the receiver's inference about the winner and a loser if this exit price were the second highest bid.

In the second-price auction, no increasing price clock bounds the second highest bid. First, in case of winning, a high valuation bidder must consider the possibility of paying the bid of a very low valuation bidder when winning, consequently being inferred as the expected value of any type above the latter by the receiver. The benefits of the potentially lower payment are compensated by the low inference by the receiver. In the case of losing the auction, a bidder can bound the receiver's inference about her type from below by means of her own bid. Compared to the English auction, this provides an additional marginal benefit to bidding in the second-price auction, which disappears as  $v$  approaches  $\bar{v}$  (for which the probability of losing goes to zero).

**Example 4 (Uniform on  $[0, 1]$ )** For  $F$  the uniform distribution, equality (5) becomes

$$v - \beta(\tilde{v}) + \frac{1 + \tilde{v}}{2} = \frac{\tilde{v}}{n-1} + \frac{n-2}{n-1} \frac{\tilde{v}}{2},$$

which implies the D1 PBE exit rule

$$\beta(v) = \frac{1}{2} + \frac{2n-3}{2(n-1)}v.$$

## 6 Expected revenue comparison

We now compare the expected revenue of the four auction designs analyzed so far. We denote the expected revenue by  $ER^k$ , with  $k = I, II, E, A$  indicating respectively first-price auction, the second-price auction, the English auction and the all-pay auction. As pointed out in Section 3, the all-pay and first-price auctions are equivalent in terms of expected payments, such that  $ER^I = ER^A$ . The following proposition shows that for finite  $n$ , we obtain a strict ranking in term of expected revenue of the English, first-price and second-price auctions.

**Proposition 5 (Expected revenue ranking)** *If  $f'(\cdot) \leq 0$  and  $n \geq 4$ , and if  $n$  is finite, then in the D1 PBE:*

$$ER^{II} > ER^I > ER^E.$$

The following example illustrates this strict expected revenue ranking for  $F$  being the uniform distribution.

**Example 5 (Uniform on  $[0, 1]$ )** *For the uniform distribution on  $[0, 1]$ , Figure 6 represents the D1 PBE bidding functions for the auction formats studied so far. The expected revenue of the first-price, second-price and English auctions is then:*

$$ER^I = ER^A = \frac{3n-1}{2n} \int_0^1 v dv^n = \frac{3n-1}{2(n+1)},$$

$$\begin{aligned} ER^{II} &= \frac{n(n-1)}{2(n-1)} \int_0^1 (2n-1 + (n-3)v) (v^{n-2} - v^{n-1}) dv \\ &= \frac{3(n-1)n+2}{2(n^2-1)} \end{aligned}$$

and

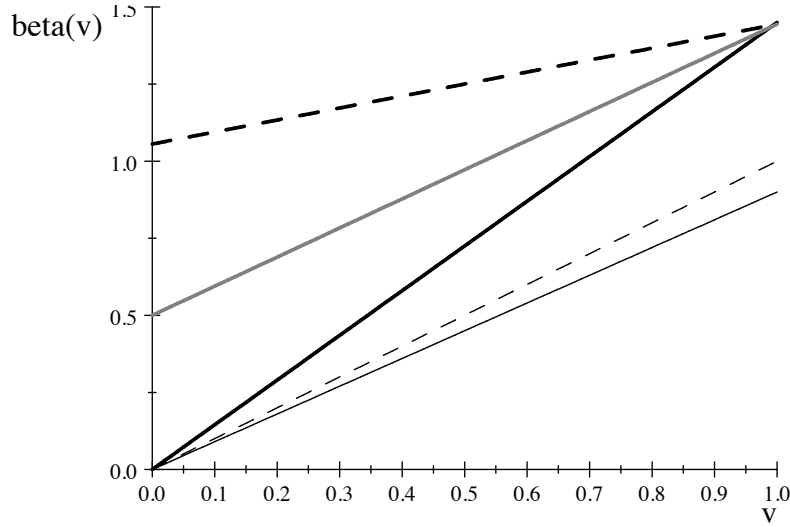
$$ER^E = \frac{1}{2} + \frac{n(2n-3)}{2} \left( \int_0^1 v^{n-1} dv - \int_0^1 v^n dv \right) = \frac{1}{2} + \frac{(2n-3)}{2(n+1)}$$

such that the first-price auction outperforms the English auction,

$$ER^E - ER^I = \frac{1}{2} + \frac{(2n-3)}{2(n+1)} - \frac{3(n-1)n+2}{2(n^2-1)} = -\frac{n}{n^2-1} < 0,$$

and but is outperformed by the second-price auction:

$$ER^{II} - ER^I = \frac{3(n-1)n+2}{2(n^2-1)} - \frac{3n-1}{2(n+1)} = \frac{1}{2(n-1)} > 0.$$



The D1 PBE bidding for  $U[0, 1]$  with  $n = 10$ , for the first-price (solid), second-price (dashed) and English (grey) auctions, with (bold) and without (thin) prestige motives.

This strict ranking in terms of expected revenues reflects the different amounts of information which are available to the receiver and the bidders in the different auction formats. The absence of a price clock in the sealed bid second-price auction implies an additional marginal benefit of a higher bid in comparison with the English auction: one's bid constrains the receiver's expected inference in case of losing the auction from below. Because of this additional effect, the equilibrium bids are strictly lower in the English auction than in the second-price auction for all bidders with a valuation strictly below the upper bound  $\bar{v}$ . Since the winner pays the bid of the second highest bidder in both auctions, the second-price auction dominates the English auction.

At the other hand, the uniform example shows that the equilibrium bidding function of the first-price auction can be strictly above that of the English auction near the upper bound  $\bar{v}$ . The reason is that the gap in terms of the receiver's expected inference between winning and losing is smaller in the English auction. At the one hand, when quitting at  $\lim_{v \rightarrow \bar{v}} \beta(v)$  losing  $\bar{v}$  types are interpreted as  $\frac{\bar{v}}{n-1} + \frac{n-2}{n-1}E(V)$  in the English auction rather than as  $E(V)$  in the first-price auction. At the other hand, when staying at  $\lim_{v \rightarrow \bar{v}} \beta(v)$  in the English auction or bidding  $\lim_{v \rightarrow \bar{v}} \beta(v)$  in the first-price auction, a winning  $\bar{v}$  type is in both auctions inferred to be a  $\bar{v}$  type. Moreover, bidders pay their own bid in the first-price auction, and that of the second highest bidder in the English auction. This is sufficient for the first-price auction to outperform the English auction in expectation, but insufficient for it to dominate the second-price auction.

However, expected revenue equivalence is preserved asymptotically for  $n$  going to infinity. To see this, note that in the limit the bid of the  $\bar{v}$  type is identical in all auctions:

$$\lim_{n \rightarrow +\infty} \lim_{v \rightarrow \bar{v}} \beta^k(v) = 2\bar{v} - E(V)$$

for  $k = I, II, E, A$ . If  $n \rightarrow \infty$ , both the winner of the auction and the second highest bidder have type  $\bar{v}$  with probability 1. As such, the  $\bar{v}$  type winner pays her own bid in all auctions. In addition, the  $\bar{v}$  type's winning bid must make her indifferent between winning and losing, because another bidder with a valuation of almost  $\bar{v}$  type would otherwise benefit from outbidding her. Under such perfect competition, the  $\bar{v}$  type's winning bid equals the sum of her valuation for the object  $\bar{v}$  and the difference in the receiver's inference about the winner and a loser,  $\bar{v} - E(V)$ , in all auction formats.

**Proposition 6 (Asymptotic revenue equivalence)** *If  $f'(\cdot) \leq 0$ , then in the D1 PBE*

$$\lim_{n \rightarrow +\infty} ER^{II} = \lim_{n \rightarrow +\infty} ER^E = \lim_{n \rightarrow +\infty} ER^I = \lim_{n \rightarrow +\infty} ER^A = 2\bar{v} - E(V).$$

Hence, expected revenue equivalence is only asymptotically valid in the presence of prestige motives.

## 7 Conclusions

Prestige or status is an important motivation for bidding in art or charity auctions. We have formalized prestige motives by making all bidders care about the expected value of the beliefs about their type of an outside party, who observes the identity and payment of the auction's winner. We have studied the bidding equilibrium and expected revenues in 4 well known auction formats: the first-price, second-price, all-pay and English auctions. We show that if the outside party's beliefs satisfy the common refinement criterion (D1) and if the type distribution function is concave, then any equilibrium bidding function must be fully separating. Moreover, we obtain a strict ranking of the expected revenues of these auction formats for a finite number of bidders. The first-price and all-pay auctions, which are equivalent in terms of expected payments, do strictly better than the English auction and strictly worse than the second-price auction. Revenue equivalence is only restored asymptotically, if the number of bidders goes to infinity.

These differences in expected revenues stem from the differences in information for the receiver and the bidders in the different auction formats. First, in the second-price and English auctions, the winner does

not pay her own bid, such that the winner's payment only imposes a lower bound on the receiver's expected beliefs about the winner's type. This incites the lowest valuation types to bid considerably above their valuation. The reason is that if they win the auction, they pay the bid of an even lower type, while the receiver's expected inference about the winner is just above the average valuation and the expected inference about the losers is close to the lowest possible valuation. In the first-price auction, in contrast, a winning low valuation bidder reveals her true low type.

Second, the highest types can bid higher in the first-price auction than in the English auction, because the gap in terms of expected inferences by the receiver between winning and losing the auction is larger in the former. Moreover, the winner has to pay her own bid in the first-price auction. This explains the superiority of the first-price over the English auction.

Third, the increasing price clock in the English auction constrains the set of potential second highest bidders at each moment. If the auction has no winner at a certain price, then the second highest bidder in the auction is at least willing to pay this price. In the sealed bid auctions, such a constraint is absent and a bidder can only depend on her own bid to constrain the expected inference of the receiver about her in the case of her losing the auction. This additional return to bidding in sealed bid auctions explains the superiority of the second-price auction over the English auction. This additional effect, inciting the lowest types to bid even more than in the English auction, also explains the superiority of the second-price auction over the first-price auction.

In short, we show that the auction format affects the performance of the auction in terms of expected revenue if bidders care about prestige. Although we believe that our setting, with risk neutral bidders, a receiver who observes the identity and payment of the winner to form beliefs about all bidders and the comparison 4 standard auction formats, is a natural and interesting benchmark case, a broad variety of alternative settings may be of interest as well. In terms of information, a receiver might only infer the type of the winner, observe all payments or the overall revenue of the auction (which would particularly change the analysis of the all-pay auction), observe all bids, only intervals of bids or rankings of bidders in terms of bids, etc. Moreover, in the absence of a general mechanism design approach, a long list of different auction formats may deserve our attention. Entry fees can offer an additional instrument for outside parties to distinguish between different bidder types, and many different forms of dynamic auctions seem particularly interesting in this setting, including all the specificities of art auctions



formats. Moreover, the receiver may process her information in different ways and bidders may care in different ways about the inferences of receiver (as in e.g. Goeree (2003)). The most interesting specification in terms of auction format and information setting depends on the specific application, but the present analysis illustrates for a few standard textbook auctions that the auction format matters in the presence of prestige motives. If prestige is indeed as important for the market of art and collectibles as Mandel (2009) suggests, then empirical studies of art auctions as well as field experiments should also take media exposure and the information setting into account.

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## A Appendix

### A.1 Proof of Lemma 1

We proceed in three steps: 1. for any D1 PBE the bidding function  $\beta$  is weakly increasing, 2. In any D1 PBE, there is no pooling with the  $\underline{y}$  type and 3. In any D1 PBE, there is no pooling above the  $\underline{y}$  type.

**Claim 1 ( $\beta$  weakly increasing)** *In any D1 PBE, if type  $v'$  chooses  $b'$ , then no  $v'' < v'$  bids  $b'' > b'$ .*

**Proof.** To save on notation, let  $p(b)$  denote the probability of winning the auction with bid  $b$  and  $E_w(b)$  and  $E_l(b)$  the expected values of the receiver's inference about respectively a winning and losing bidder who bids  $b$ . Assume that type  $v'$  bids  $b'$  in equilibrium and gets expected inferences  $E_w(b')$  and  $E_l(b')$ . Let  $(E''_w, E''_l)$  a pair of inferences such that type  $v'$  is indifferent between bidding  $b''$  and getting inference  $(E''_w, E''_l)$  and her equilibrium payoff, i.e.

$$\begin{aligned} p(b')(v' - b') + E_l(b') + p(b')[E_w(b') - E_l(b')] \\ = p(b'')(v' - b'') + E''_l + p(b'')[E''_w - E''_l] \end{aligned}$$

or

$$\begin{aligned} [p(b'') - p(b')]v' = A \equiv p(b'')b'' - p(b')b' + E_l(b') + \\ p(b')[E_w(b') - E_l(b')] - (E''_l + p(b')[E''_w - E''_l]) \end{aligned}$$

and note that  $p(b'') - p(b') \geq 0$ . Then if  $p(b'') - p(b') > 0$ , it must be that

$$[p(b'') - p(b')]v'' < A,$$

such that

$$p(b')(v'' - b') + E_l(b') + p(b')[E_w(b') - E_l(b')] > p(b'')(v'' - b'') + E''_l + p(b'')[E''_w - E''_l].$$

Hence, the lower valuation type needs a higher compensation in terms of inference for a higher bid.

Assume then that the equilibrium expected utility of type  $v''$  is low enough to make  $M^+(b'', v') \subseteq M^+(b'', v'') \cup M^0(b'', v'')$ . Then it must be that the  $v''$  strictly prefers bundle  $(b', E_w(b'), E_l(b'))$  to her equilibrium strategy, a contradiction. Therefore  $\mu(v''|b'') = 0$  in the D1 PBE, and no  $v''$  type with  $v'' < v'$  chooses a  $b''$  bid with  $b'' > b'$  if type  $v'$  bids  $b'$  in equilibrium. ■

**Claim 2 (No pooling with  $\underline{v}$ )** *No type  $v > \underline{v}$  pools with type  $\underline{v}$  in the D1 PBE.*

Assume an equilibrium in which a non-degenerate set of types  $O = \{v|\beta(v) = \tilde{b}\}$  pool at  $\tilde{b}$ , such that  $\underline{v} \in O$ . By Claim 1,  $O$  is a convex set. If  $\tilde{b} > \underline{v}$ , then a type  $\underline{v}$  bidder can strictly improve herself by deviating to  $\underline{v}$ . Such deviation is never observed, such that the receiver's inference about the  $\underline{v}$  bidder is not worse, but she avoids winning the auction to

pay  $\tilde{b}$  in excess of her valuation  $\underline{v}$ .

If  $\tilde{b} \leq \underline{v}$ , then note that the expected inference about a bidder in  $O$  is  $E_w(\tilde{b}) = \frac{1}{|O|} \int_O v dF(v)$  and  $E_l(\tilde{b})$ . The probability of winning when pooling at  $\tilde{b}$  is  $\frac{F(\sup(O))^{n-1}}{n}$ . Consider then type  $\sup(O)$ . If she bids a  $\tilde{b} + \varepsilon$ , with  $\varepsilon > 0$ , she wins at least with probability  $F(\sup(O))^{n-1}$ , in which case  $E_w(\tilde{b} + \varepsilon) \geq \sup(O)$  and  $E_l(\tilde{b} + \varepsilon) > E_l(\tilde{b})$ , while  $\sup(O) - \tilde{b} - \varepsilon > 0$  for  $\varepsilon$  sufficiently small. But in equilibrium it must be that

$$\begin{aligned} & \frac{F(\sup(O))^{n-1}}{n} \left( \sup(O) - \tilde{b} + E_w(\tilde{b}) \right) + \left( 1 - \frac{F(\sup(O))^{n-1}}{n} \right) E_l(\tilde{b}) \\ & \geq F(\sup(O))^{n-1} \left( 2\sup(O) - \tilde{b} - \varepsilon \right) + (1 - F(\sup(O))^{n-1}) E_l(\tilde{b} + \varepsilon), \end{aligned}$$

which is only true for  $\varepsilon \rightarrow 0$  if  $\sup(O) = \underline{v}$  and  $n = 1$ .

**Claim 3 (No pooling above  $\underline{v}$ )** *In the D1 PBE, no bid  $\tilde{b}$  is chosen by two types  $v' \neq v''$ .*

**Proof.** Assume a D1 PBE in which  $\tilde{b}$  is the lowest bid chosen by a nondegenerate set of types  $O = \{v | \beta(v) = \tilde{b}\}$ . Note that  $O$  is convex by Claim 1 and  $\inf(O) > \underline{v}$  by Claim 2. By the continuity of  $f$  and of the utility function w.r.t. all arguments, the  $\inf(O)$  must in equilibrium be indifferent between separating at  $\lim_{v \rightarrow \inf(O)^-} \beta(v)$  and pooling at  $\tilde{b}$ . Note then that the indirect utility difference between  $\sup(O)$  and  $\inf(O)$  in the pooling equilibrium is

$$p(\tilde{b}) (\sup(O) - \inf(O)).$$

In the separating equilibrium this is by the envelope theorem

$$\int_{\inf(O)}^{\sup(O)} F^{n-1}(x) dx = \sup(O) F^{n-1}(\sup(O)) - \inf(O) F^{n-1}(\inf(O)) - \int_{\inf(O)}^{\sup(O)} x dF^{n-1}(x).$$

We now show that

$$\int_{\inf(O)}^{\sup(O)} F^{n-1}(x) dx > p(\tilde{b}) (\sup(O) - \inf(O)) \quad (8)$$

if  $f'(\cdot) \leq 0$ .

First write the probability of winning the auction while bidding  $\tilde{b}$

$$p(\tilde{b}) = \sum_{i=0}^{n-1} \binom{n-1}{i} \frac{F^{n-1-i}(\inf(O)) (F(\sup(O)) - F(\inf(O)))^i}{i+1}.$$

Note then that  $p(\bar{b})(\sup(O) - \inf(O)) = \int_{\inf(O)}^{\sup(O)} F^{n-1}(x) dx = 0$  for  $\sup(O) = \inf(O)$ . Differentiate both sides of (8) to  $\sup(O)$ , to obtain

$$\frac{\partial p(\bar{b})}{\partial \sup(O)} (\sup(O) - \inf(O)) + p(\bar{b}) < F^{n-1}(\sup(O)),$$

which can be written as

$$\alpha [F^{n-1}(\sup(O)) - p(\bar{b}) - F^{n-1-i}(\inf(O))] < F^{n-1}(\sup(O)) - p(\bar{b}), \quad (9)$$

with

$$\alpha = \frac{f(\sup(O))}{\frac{F(\sup(O)) - F(\inf(O))}{\sup(O) - \inf(O)}}$$

because

$$\begin{aligned} \frac{\partial p(\bar{b})}{\partial \sup(O)} &= \sum_{i=1}^{n-1} \binom{n-1}{i} F^{n-1-i}(\inf(O)) (F(\sup(O)) - F(\inf(O)))^{i-1} \frac{i}{i+1} f(\sup(O)) \\ &= [F^{n-1}(\sup(O)) - p(\bar{b}) - F^{n-1-i}(\inf(O))] \frac{f(\sup(O))}{(F(\sup(O)) - F(\inf(O)))}, \end{aligned}$$

in which the last equality uses

$$1 - p(\bar{b}) = (1 - F^{n-1}(\sup(O))) + \sum_{i=0}^{n-1} \binom{n-1}{i} F^{n-1-i}(\inf(O)) (F(\sup(O)) - F(\inf(O)))^i \frac{i}{i+1}.$$

Note then that  $f'(\cdot) \leq 0$  implies  $\alpha \leq 1$ , such that (9) and therefore (8) are always satisfied for  $F(\sup(O)) > F(\inf(O))$  and  $f'(\cdot) \leq 0$ . Then the  $\sup(O)$  type can achieve a strictly higher expected utility if she would deviate to the bid she makes in the fully separating equilibrium because the expected inference after such a deviation is at least the expected inference she gets in the fully separating equilibrium. This excludes any different types pooling in a D1 PBE. ■

## A.2 Proof of Proposition 1

We proceed again in 3 steps: 1. establish shape of the bidding function; 2. show that  $\beta'(\cdot) > 0$  implies that the second order condition is satisfied and 3. show that  $\beta'(\cdot) > 0$ .

**Claim 4 (Bidding function)**  $\beta$  is as written in Proposition 1.

**Proof.** Substitute  $\tilde{v} = v$  in (2) to obtain

$$\frac{\partial}{\partial v} (\beta(v) F^{n-1}(v)) = 2v (F^{n-1}(v))' + F^{n-1}(v) - \int_{\underline{v}}^v x dF(x) (F^{n-1}(v))'.$$

Integrate and divide both sides by  $F^{n-1}(\tilde{v})$  to find

$$\begin{aligned} \beta(v) &= \frac{2}{F^{n-1}(v)} \int_{\underline{v}}^v x dF^{n-1}(x) + \frac{1}{F^{n-1}(v)} \int_{\underline{v}}^v F^{n-1}(x) dx \\ &\quad - \frac{1}{F^{n-1}(v)} \int_{\underline{v}}^v \frac{1}{F(y)} \int_{\underline{v}}^y x dF(x) dF^{n-1}(y). \end{aligned} \quad (10)$$

Apply partial integration on the second and last RHS term in (10), to obtain respectively

$$\frac{1}{F^{n-1}(v)} \int_{\underline{v}}^v F^{n-1}(x) dx = v - \frac{1}{F^{n-1}(v)} \int_{\underline{v}}^v x dF^{n-1}(x)$$

and

$$\begin{aligned} &\frac{1}{F^{n-1}(v)} \int_{\underline{v}}^v \frac{1}{F(y)} \int_{\underline{v}}^y x dF(x) d(F^{n-1}(y)) \\ &= \frac{n-1}{F^{n-1}(v)} \int_{\underline{v}}^v \int_{\underline{v}}^y x dF(x) (F^{n-3}(y)) dF(y) \\ &= \frac{n-1}{n-2} \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} - \frac{1}{n-2} \frac{\int_{\underline{v}}^v x dF^{n-1}(x)}{F^{n-1}(x)}, \end{aligned}$$

and substitute these in (10) to obtain

$$\beta(v) = v + \frac{n-1}{n-2} \left( \frac{\int_{\underline{v}}^v x dF^{n-1}(x)}{F^{n-1}(v)} - \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right).$$

To find the lower bound in the first-price auction, note that by the intermediate value theorem two values  $v_1$  and  $v_2$  exist such that

$$\beta(v) = v - \frac{n-1}{n-2} \left( v_1 \frac{\int_{\underline{v}}^v dF(x)}{F(v)} - v_2 \frac{\int_{\underline{v}}^v dF^{n-1}(x)}{F^{n-1}(v)} \right)$$

Moreover,

$$\lim_{v \rightarrow \underline{v}^+} v_1 = \lim_{v \rightarrow \underline{v}^+} v_2 = \underline{v},$$

such that  $\lim_{v \rightarrow \underline{v}^+} \beta(v) = \underline{v}$ . ■

**Claim 5 (Second order condition)** *The second order conditions are satisfied iff  $\beta'(\cdot) > 0$*

**Proof.** We first show that a strictly increasing bidding function implies local strict concavity of the bidder's problem, and then that the equilibrium bid is a global expected utility maximizing choice for each bidder. First, use the first order condition (2) to define

$$G(\tilde{v}, v) \equiv (F^{n-1}(\tilde{v}))' (v - \beta(\tilde{v}) + \tilde{v}) + (1 - \beta'(\tilde{v})) (F^{n-1}(\tilde{v})) - \frac{1}{F(\tilde{v})} \int_{\underline{v}}^{\tilde{v}} x dF(x) (F^{n-1}(\tilde{v}))' = 0,$$

which defines  $\beta(v)$  for  $\tilde{v} = v$ . By the implicit function theorem  $\beta'(v) > 0$  if and only if strictly higher  $v$  prefer to imitate a strictly higher  $\tilde{v}$ , i.e. if

$$-\frac{G_2(\tilde{v}, v)}{G_1(\tilde{v}, v)} = -\frac{(F^{n-1}(\tilde{v}))'}{G_1(\tilde{v}, v)} > 0,$$

which is only satisfied if  $G_1(\tilde{v}, v) < 0$  for all  $v$  at  $\tilde{v} = v$ .

By construction,  $G(\tilde{v}, v) = 0$  is satisfied at  $\tilde{v} = v$ , while  $G_2(\tilde{v}, v) > 0$  for all  $\tilde{v} > v$ , such that type  $v$ 's utility reaches a unique maximum at  $\tilde{v} = v$ . ■

**Claim 6 (Strictly increasing  $\beta$ )**  $\beta$  is strictly increasing.

**Proof.** Write

$$\begin{aligned} \beta'(v) &= 1 + \frac{n-1}{n-2} \frac{f(v)}{F(v)} \left( (n-1) \left( v - \frac{\int_{\underline{v}}^v x dF^{n-1}(x)}{F^{n-1}(v)} \right) - \left( v - \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right) \right) \\ &= 1 + \frac{n-1}{n-2} \frac{f(v)}{F(v)} \left( (n-1) \frac{\int_{\underline{v}}^v F^{n-1}(x) dx}{F^{n-1}(v)} - \frac{\int_{\underline{v}}^v F(x) dx}{F(v)} \right), \end{aligned}$$

with the last equation by partial integration. To see that

$$(n-1) \frac{\int_{\underline{v}}^v F^{n-1}(x) dx}{F^{n-1}(v)} - \frac{\int_{\underline{v}}^v F(x) dx}{F(v)} \geq 0,$$

note that this term is 0 for  $n = 2$ , and that

$$\begin{aligned} &\frac{\partial}{\partial n} \left( (n-1) \frac{\int_{\underline{v}}^v F^{n-1}(x) dx}{F^{n-1}(v)} \right) \\ &= \frac{\int_{\underline{v}}^v F^{n-1}(x) dx}{F^{n-1}(v)} + \frac{(n-1)^2}{F(v)} \left( \frac{\int_{\underline{v}}^v F^{n-2}(x) dx}{F^{n-2}(v)} - \frac{\int_{\underline{v}}^v F^{n-1}(x) dx}{F^{n-1}(v)} \right) > 0, \end{aligned}$$

such that  $\beta'(v) > 1$  for  $n \geq 3$ . ■

### A.3 Proof of Proposition 2

The proof that all D1 PBE bidding functions of the all-pay auction satisfy  $\beta'(\cdot) > 0$  is almost identical to the proof of Lemma 1, and therefore omitted. Let denote  $EP^k(\tilde{v})$  denote the expected payment of a bidder choosing type  $\tilde{v}$ 's equilibrium bid, with  $k = I, A$  indicating resp. the first-price and all-pay auction. Let

$$E(\tilde{v}) = F^{n-1}(\tilde{v})\tilde{v} + (1 - (F^{n-1}(\tilde{v}))) \frac{\int_{\tilde{v}}^{\bar{v}} \frac{1}{F(y)} \int_{\underline{v}}^y x dF(x) dF^{n-1}(y)}{(1 - (F^{n-1}(\tilde{v})))}$$

represent the receiver's expected inference about a bidder choosing type  $\tilde{v}$ 's equilibrium bid. Then the expected payoff of a valuation  $v$  bidder choosing a  $\tilde{v}$  type's equilibrium bid is

$$F(\tilde{v})^{n-1}v - EP^k(\tilde{v}) + E(\tilde{v}).$$

The first order condition for expected payoff maximization is

$$(F(\tilde{v})^{n-1})'v - (EP^k(\tilde{v}))' + (E(\tilde{v}))' = 0.$$

Substituting  $\tilde{v} = v$  solving for  $EP^k$ , we obtain

$$EP^k(v) = EP^k(v) + \int_v^v x dF(x)^{n-1} + \int_v^v (E(x))' dx$$

As  $EP^I(v) = F(v)^{n-1}\beta^I(v)$ ,  $EP^A(v) = \beta^A(v)$  and  $EP^I(\underline{v}) = EP^A(\underline{v}) = 0$ , it follows that  $\beta^A(v) = F(v)^{n-1}\beta^I(v)$ .

### A.4 Proof of Lemma 2

This proof proceeds in the same 3 steps as the proof of Lemma 1, and the first and third step are similar to those in the proof of Lemma 1. Let  $\Pr(1|b)$ ,  $\Pr(2|b)$  and  $\Pr(3|b) = 1 - \Pr(1|b) - \Pr(2|b)$  resp. denote the probabilities of winning, having the second highest bid and having a lower bid with bid  $b$ , and let  $E^1(b)$ ,  $E^2(b)$  and  $E^l(b)$  be the expected inferences of the receiver if a bidder with bid  $b$  resp. wins, has the second highest bid and loses, and let  $E^p(b)$  be the expected payment of a winner with bid  $b$ .

**Claim 7 (Weakly increasing)** *If a  $v'$  type bids  $b'$  in equilibrium, then no  $v'' < v'$  bids  $b'' > b'$  in equilibrium.*

**Proof.** Assume the opposite. Because both  $b'$  and  $b''$  are sent in equilibrium, it must be that  $\Pr(1|b'') > \Pr(1|b')$ . Then if  $v''$  bids  $b''$  in



equilibrium, it must be that

$$\begin{aligned}
& \Pr(1|b'') (v'' - E^p(b'') + E^1(b'')) + \Pr(2|b'') E^2(b'') \\
& + (1 - \Pr(1|b'') - \Pr(2|b'')) E^l(b'') \\
& \geq \Pr(1|b') (v'' - E^p(b') + E^1(b')) \\
& + \Pr(2|b') E^2(b') + (1 - \Pr(1|b') - \Pr(2|b')) E^l(b').
\end{aligned}$$

But given that  $\Pr(1|b'') > \Pr(1|b')$ , this implies that the  $v'$  type strictly prefers a  $b''$  bid above  $b'$ , which contradicts the equilibrium. Assume then that in equilibrium the  $v''$  type's equilibrium expected utility is so low that  $M^+(b'', v') \subseteq M^+(b'', v'') \cup M^0(b'', v'')$ , then it must be that the  $v''$  strictly prefers the bundle  $(b', E^1(b'), E^2(b'), E^l(b'), E^p(b'))$  to her equilibrium strategy, a contradiction. Hence, if type  $v'$  bids  $b'$  in equilibrium, then  $\mu(v''|b'') = 0$ , and no  $v''$  type with  $v'' < v'$  chooses a  $b''$  bid, with  $b'' > b'$ . ■

**Claim 8 (No pooling with  $\underline{v}$ )** *In the D1 PBE, no other type pools with  $\underline{v}$ .*

**Proof.** Suppose a nondegenerate set of types  $O = \{v | \beta(v) = \tilde{b}\}$ , with  $\underline{v} \in O$ , pool in equilibrium at bid  $\tilde{b}$ . If  $n \geq 3$ , then if type  $\underline{v}$  (or a type just above her) deviates to a bid  $\tilde{b} - \varepsilon$ , for  $\varepsilon > 0$ , she has zero probability of having the highest or second highest bid, while the expected inference if she loses remains unchanged at  $E^l(\tilde{b})$ . In equilibrium, such a deviation cannot be profitable such that:

$$\Pr(1|\tilde{b}) (\underline{v} - \tilde{b} + E^1(\tilde{b})) + \Pr(2|\tilde{b}) E^2(\tilde{b}) + (1 - \Pr(1|\tilde{b}) - \Pr(2|\tilde{b})) E^l(\tilde{b}) \geq E^l(\tilde{b})$$

or that

$$\frac{\Pr(1|\tilde{b})}{\Pr(1|\tilde{b}) + \Pr(2|\tilde{b})} (\underline{v} - \tilde{b} + E^1(\tilde{b})) + \frac{\Pr(2|\tilde{b})}{\Pr(1|\tilde{b}) + \Pr(2|\tilde{b})} E^2(\tilde{b}) \geq E^l(\tilde{b}).$$

Note that because  $E^2(\tilde{b}) \leq E^l(\tilde{b})$ , it must be that

$$\underline{v} - \tilde{b} + E^1(\tilde{b}) \geq E^2(\tilde{b}). \quad (11)$$

If the sup( $O$ ) type would deviate to a bid  $\tilde{b} + \varepsilon$ , for  $\varepsilon > 0$  small enough such that  $\tilde{b} + \varepsilon$  is out-of-equilibrium and no equilibrium bids are in  $(\tilde{b}, \tilde{b} + \varepsilon)$ , she still pays  $\tilde{b}$  and gets expected inference  $E^1(\tilde{b})$  if winning,

is inferred as  $E^2(\tilde{b} + \varepsilon) > E^2(\tilde{b})$  if having the second highest bid and has expected inference  $E^l(\tilde{b} + \varepsilon)$  if losing. For  $\sup(O)$  to bid  $\tilde{b}$  in equilibrium, it must be that

$$\begin{aligned} & \Pr(1|\tilde{b} + \varepsilon) \left( \sup(O) - \tilde{b} + E^1(\tilde{b}) \right) + \\ & \Pr(2|\tilde{b} + \varepsilon) E^2(\tilde{b} + \varepsilon) + \left( 1 - \Pr(1|\tilde{b} + \varepsilon) - \Pr(2|\tilde{b} + \varepsilon) \right) E^l(\tilde{b} + \varepsilon) \leq \\ & \Pr(1|\tilde{b}) \left( \sup(O) - \tilde{b} + E^1(\tilde{b}) \right) + \Pr(2|\tilde{b}) E^2(\tilde{b}) + \Pr(3|\tilde{b}) E^l(\tilde{b}). \end{aligned} \quad (12)$$

Note then that

$$E^l(\tilde{b}) = \frac{\Pr(3|\tilde{b} + \varepsilon)}{\Pr(3|\tilde{b})} E^l(\tilde{b} + \varepsilon) + \frac{\Pr(3|\tilde{b}) - \Pr(3|\tilde{b} + \varepsilon)}{\Pr(3|\tilde{b})} E^2(\tilde{b}), \quad (13)$$

i.e. if the  $\sup(O)$  type is neither winning nor second when pooling at  $\tilde{b}$ , then the second highest bidder either has a higher valuation or she is in  $O$ . In the former case, the receiver's expected inference is  $E^l(\tilde{b} + \varepsilon)$ . In the latter case it must be  $E^2(\tilde{b})$ . Substituting (13) this in (12), we obtain

$$\begin{aligned} & \left( \Pr(1|\tilde{b} + \varepsilon) - \Pr(1|\tilde{b}) \right) \left( \sup(O) - \tilde{b} + E^1(\tilde{b}) - E^2(\tilde{b}) \right) + \\ & \Pr(2|\tilde{b} + \varepsilon) \left( E^2(\tilde{b} + \varepsilon) - E^2(\tilde{b}) \right) \leq 0, \end{aligned}$$

which can only be satisfied is  $\sup(O) = \underline{v}$ . ■

**Claim 9 (No Pooling)** *In the D1 PBE there is no pooling at bids strictly above  $\underline{v}$ .*

**Proof.** Assume that  $\tilde{b}$  is the lowest bid at which a nondegenerate set of types  $O = \{v | \beta(v) = \tilde{b}\}$  pool. The same envelope theorem argument as for the first-price auction also works for the second. Note then again that the expected utility difference between  $\sup(O)$  and  $\inf(O)$  while pooling at  $\tilde{b}$  is  $p(1|\tilde{b}) (\sup(O) - \inf(O))$ , while in separation this is by the envelope theorem

$$\int_{\inf(O)}^{\sup(O)} F^{N-1}(x) dx = \sup(O) F^{N-1}(\sup(O)) - \inf(O) F^{N-1}(\inf(O)) - \int_{\inf(O)}^{\sup(O)} x dF^{N-1}(x).$$

If  $\inf(O) = \sup(O)$ , these are both equal to zero, but by the same differential argument as for Claim 3,

$$p(\bar{b})(\sup(O) - \inf(O)) < \int_{\inf(O)}^{\sup(O)} F^{N-1}(x) dx.$$

The condition  $f'(\cdot) \leq 0$ , imposed to guarantee the existence of a separating equilibrium, always guarantees this inequality. ■

## A.5 Proof of Proposition 3

The proof proceeds in three steps: deriving the bidding function, showing that the second order condition is satisfied if the bidding functions is strictly increasing and showing that the proposed bidding function is strictly increasing. The second step is almost identical to Claim 5, and is omitted.

**Claim 10 (Bidding function)**  $\beta$  is as written in Proposition 3

**Proof.** From (4), collect terms to obtain

$$\beta(v) = \frac{n-2}{n-1} \frac{1}{F(v)} \left( v - \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right) + \frac{\int_v^{\bar{v}} x dF(x)}{1-F(v)} + \frac{1}{(n-1)} \frac{(1-F(v))}{f(v)} \quad (14)$$

$$= \frac{n-2}{n-1} \frac{\int_{\underline{v}}^v F(x) dx}{F^2(v)} + \frac{1}{(n-1)} \frac{\int_v^{\bar{v}} f(x) dx}{f(v)} + \frac{\int_v^{\bar{v}} x dF(x)}{1-F(v)}, \quad (15)$$

where (15) is obtained from (14) by partially integrating the first term.

Then by L'Hôpital's rule,  $\lim_{v \rightarrow \underline{v}} \frac{\int_{\underline{v}}^v F(x) dx}{F^2(v)} = \frac{F(\underline{v})}{2F(\underline{v})f(\underline{v})}$ , while  $\lim_{v \rightarrow \bar{v}} \frac{\int_v^{\bar{v}} x dF(x)}{1-F(v)} = \frac{-\bar{v}f(\bar{v})}{-f(\bar{v})} = \bar{v}$ , such that

$$\begin{aligned} \lim_{v \rightarrow \underline{v}} \beta(v) &= E(V) + \frac{n}{2(n-1)f(\underline{v})} \\ \lim_{v \rightarrow \bar{v}} \beta(v) &= \bar{v} + \frac{n-2}{n-1}(\bar{v} - E(V)). \end{aligned}$$

■

**Claim 11 (Second order condition)** The second order condition is satisfied iff  $\beta'(\cdot) > 0$ .

**Proof.** The proof that  $\beta'(\cdot) > 0$  implies that the second order condition is satisfied is identical to that of Claim 5. ■

**Claim 12 (Strictly increasing  $\beta$ )**  $\beta$  is strictly increasing if  $n \geq 4$  and  $f'(\cdot) \leq 0$  or if  $n = 3$  and  $f'(\cdot) < 0$ .

**Proof.** Write

$$\begin{aligned} \beta'(v) = & \frac{n-2}{n-1} \frac{1}{F(v)} \left( 1 - 2f(v) \frac{\int_v^v F(x) dx}{F^2(v)} \right) + \frac{f(v)}{1-F(v)} \left( \frac{\int_v^{\bar{v}} x dF(x)}{1-F(v)} - v \right) \\ & - \frac{1}{(n-1)} \left( 1 + \frac{f'(v) \int_v^{\bar{v}} f(x) dx}{(f(v))^2} \right), \end{aligned} \quad (16)$$

and apply partial integration on the second RHS term in (16) to find

$$\begin{aligned} \beta'(v) = & \frac{n-2}{n-1} \frac{1}{F(v)} \left( 1 - 2f(v) \frac{\int_v^v F(x) dx}{F^2(v)} \right) + \frac{f(v) \int_v^{\bar{v}} (1-F(x)) dx}{(1-F(v))^2} \\ & - \frac{1}{(n-1)} - \frac{1}{(n-1)} \frac{f'(v) \int_v^{\bar{v}} f(x) dx}{(f(v))^2}. \end{aligned} \quad (17)$$

Note then that all RHS terms in (17) are nonnegative if  $f'(\cdot) \leq 0$ , except  $-\frac{1}{(n-1)}$ . If  $f'(\cdot) < 0$  and  $v > v^\circ$ , then  $2f(v) \frac{\int_v^v F(x) dx}{F^2(v)} < \frac{\int_v^v dF^2(x)}{F^2(v)} = 1$ , such that  $1 - 2f(v) \frac{\int_v^v F(x) dx}{F^2(v)} > 0$ . At the other hand, the last term  $-\frac{1}{(n-1)} \frac{f'(v) \int_v^{\bar{v}} f(x) dx}{(f(v))^2}$  is strictly positive for  $v < \bar{v}$ . Both terms are zero for  $f'(\cdot) = 0$ . The main step is now to prove that  $f'(\cdot) \leq 0$  implies

$$\frac{f(v) \int_v^{\bar{v}} (1-F(x)) dx}{(1-F(v))^2} \geq \frac{1}{2}. \quad (18)$$

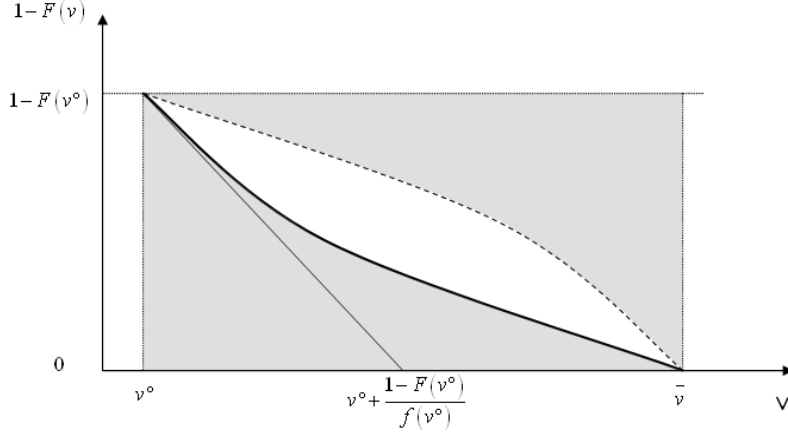
First note that  $F$  is the uniform distribution, inequality (18) is satisfied with equality. Note that  $f'(\cdot) \leq 0$  implies that  $1-F(\cdot)$  is convex and write the inequality as

$$2 \frac{\int_v^{\bar{v}} (1-F(x)) dx}{1-F(v)} \geq \frac{1-F(v)}{f(v)}. \quad (19)$$

In figure A.5, that the LHS of (19), for  $v = v^\circ$ , is the grey area divided by the distance  $1-F(v^\circ)$ . Moreover,  $\frac{\partial(1-F(v^\circ))}{\partial v^\circ} = -f(v^\circ)$ , such that this tangent line through  $(v^\circ, 1-F(v^\circ))$  crosses the X-axis at  $v^\circ + \frac{1-F(v^\circ)}{f(v^\circ)}$ . For  $f'(\cdot) = 0$ , it must be that  $v^\circ + \frac{1-F(v^\circ)}{f(v^\circ)} = \bar{v}$ , such that the inequality in (19) is always satisfied with equality. If however  $f'(v) < 0$  at some  $v > v^\circ$ , this strictly increases the LHS but not the RHS of (19), such that the inequality is strictly satisfied. Thus,  $f'(\cdot) \leq 0$  implies that

$$\frac{f(v) \int_v^{\bar{v}} (1-F(x)) dx}{(1-F(v))^2} \geq \frac{1}{2} > \frac{1}{(n-1)}.$$

Hence,  $\beta'(\cdot) > 0$  for  $n > 3$ , while for  $n = 3$ , we need  $f'(\cdot) < 0$  to guarantee  $\beta'(\cdot) > 0$ . ■



## A.6 Proof of Lemma 3

**Claim 13 ( $\beta$  weakly increasing)** *If in a D1 PBE  $v'$  exits at  $b'$ , then no  $v'' < v'$  exits at  $b'' > b'$ .*

**Proof.** Assume that  $v''$  stays until  $b''$ . If type  $v'$  exits at  $b'$ , then what she can win by staying is not better than what can be expected by exiting. The expected payoff of exiting at  $b'$  is identical for the  $v'$  and  $v''$  types, while  $v'$  benefits strictly more from winning than  $v''$ , such that  $v''$  should strictly prefer to exit at  $b'$ . ■

Assume then a PBE with  $v'$  exiting at  $b'$ ,  $v'' < v'$  and  $b'' > b'$  an out-of-equilibrium exit strategy. Then if type  $v''$  equilibrium strategy is so low that  $M^+(b'', v') \subseteq M^+(b'', v'') \cup M^0(b'', v'')$ , then type  $v''$  would strictly prefer to exit at  $b'$  above her equilibrium strategy, a contradiction. Hence,  $M^+(b'', v'') \cup M^0(b'', v'') \subset M^+(b'', v')$ , such that in any D1 PBE we have  $\beta'(\cdot) \geq 0$ .

**Claim 14 (No pooling)** *In any D1 PBE, no two types  $v' \neq v''$  exit at the same price  $\tilde{b}$ .*

Let  $\tilde{b}$  be the lowest price at which a nondegenerate set of types  $O = \{v | \beta(v) = \tilde{b}\}$  exit. By Claim 13,  $O$  is convex. For a non-degenerate set  $O$ , a sufficiently small  $\varepsilon > 0$  can be found for which the winning equilibrium payoff at price  $\tilde{b} + \varepsilon$  is strictly greater than at  $\tilde{b}$ . If  $\tilde{b} + \varepsilon$  is out-of-equilibrium, then for  $\varepsilon$  sufficiently small and  $O$  nondegenerate

$$\sup(O) - \tilde{b} - \varepsilon + \frac{\int_{\sup(O)}^{\bar{v}} x dF(x)}{1 - F(\sup(O))} > \sup(O) - \tilde{b} + \frac{\int_{\inf(O)}^{\bar{v}} x dF(x)}{1 - F(\inf(O))}, \quad (20)$$

while the expected payoff of a loser exiting at  $\tilde{b} + \varepsilon$  is at least as large as that of a loser exiting at  $\tilde{b}$ . If  $\tilde{b}$  is chosen in PBE by higher types, this increases the RHS of inequality 20. Hence,  $\beta'(\cdot) > 0$ .

## A.7 Proof of Proposition 4

Equation (7) is obtained by setting  $\tilde{v} = v$  in (5) and solving for  $\beta$ . To see that  $f'(\cdot) \leq 0$  implies  $\beta'(\cdot) > 0$ , write

$$\beta'(v) = \frac{n-2}{n-1} \left[ 1 - \frac{f(v)}{F(v)} \left( v - \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right) \right] + \frac{f(v)}{1-F(v)} \left( \frac{\int_{\underline{v}}^{\bar{v}} x dF(x)}{1-F(v)} - v \right).$$

The second RHS term is always strictly positive for  $v \in [\underline{v}, \bar{v}]$ . To see that the first RHS term is always positive, note that the term between square brackets is strictly positive if

$$F(v) > \left( v - \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right) F'(v),$$

which is always satisfied. Indeed for  $f'(\cdot) \leq 0$ ,  $F$  is concave such that  $F(v) \geq F'(v)(v - \underline{v}) \geq \left( v - \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right) F'(v)$ , with the last inequality strict for  $v \in (\underline{v}, \bar{v}]$ .

For  $\beta$  as in (7), the exit rule in (5) fixes for every  $v$  a unique  $\tilde{v}$ , as

$$\frac{\partial}{\partial \tilde{v}} \left( -\beta(\tilde{v}) + \frac{1}{1-F(\tilde{v})} \int_{\tilde{v}}^{\bar{v}} x dF(x) - \frac{\tilde{v}}{n-1} - \frac{n-2}{n-1} \frac{\int_{\underline{v}}^{\tilde{v}} x dF(x)}{F(\tilde{v})} \right) = -1.$$

Note also that no type  $v$  wishes to mimic a different type  $\tilde{v}$ . By construction  $\beta(\tilde{v})$  is such that (5) is satisfied with equality for  $v = \tilde{v}$  and such that for  $v > \tilde{v}$  the benefits of winning (LHS) are strictly greater than the RHS when mimicking  $\tilde{v}$ 's strategy. The latter is the opposite if  $v < \tilde{v}$ .

## A.8 Proof of Proposition 5

Let  $\beta^k(\cdot)$  denote the equilibrium bidding function and  $ER^k$  be the expected revenue for  $k = I, II, E$  respectively the first-price auction, the second-price auction, the English auction. We first write the expected revenue of the 3 auctions in a more convenient form.

$$\begin{aligned} ER^I &= \int_{\underline{v}}^{\bar{v}} \beta^I(x) dF^n(x) \\ &= \int_{\underline{v}}^{\bar{v}} x dF^n(y) - \frac{n-1}{n-2} \int_{\underline{v}}^{\bar{v}} \frac{\int_{\underline{v}}^y x dF(x)}{F(y)} dF^n(y) \\ &\quad + \frac{n-1}{n-2} \int_{\underline{v}}^{\bar{v}} \frac{\int_{\underline{v}}^y x dF^{n-1}(x)}{F^{n-1}(y)} dF^n(y) \end{aligned}$$

$$\begin{aligned}
&= E(V_1^{(n)}) + \frac{n-1}{n-2} E(V_2^{(n)}) - \frac{n-1}{n-2} \int_{\underline{v}}^{\bar{v}} \frac{1}{F(y)} \int_{\underline{v}}^{\bar{v}} 1_{x \leq v} x dF(x) (F^n(y))' dy \\
&= E(V_1^{(n)}) + \frac{n-1}{n-2} E(V_2^{(n)}) - \frac{(n-1)n}{n-2} \int_{\underline{v}}^{\bar{v}} \int_{\underline{v}}^{\bar{v}} 1_{x \leq v} f(y) (F^{n-2}(y)) dy x f(x) dx \\
&= \frac{n-1}{n-2} E(V_1^{(n)}) + \frac{n-1}{n-2} E(V_2^{(n)}) - \frac{n}{n-2} E(V) \tag{21}
\end{aligned}$$

The expected revenue of the second-price auction is

$$\begin{aligned}
ER^H &= \int_{\underline{v}}^{\bar{v}} \beta^H(x) d(nF^{n-1}(x) - (n-1)F^n(x)) \\
&= n(n-2) \int_v^{\bar{v}} x(1-F(x))F^{n-3}(x)f(x)dx \\
&\quad - n(n-2) \int_{\underline{v}}^{\bar{v}} \frac{\int_{\underline{v}}^y F(x) dx}{F^2(y)} (1-F(y)) F^{n-2}(y) f(y) dy \\
&\quad + n(n-1) \int_{\underline{v}}^{\bar{v}} \frac{\int_{\underline{v}}^y x dF(x)}{1-F(y)} ((1-F(y)) F^{n-2}(y) f(y)) dy \\
&\quad + n \int_{\underline{v}}^{\bar{v}} ((1-F(y))^2 F^{n-2}(y)) dy \\
&= \frac{n}{n-1} E(V_2^{(n-1)}) - \frac{n}{n-3} E(V) + \frac{n}{n-3} E(V_1^{(n-2)}) \\
&\quad - \frac{n}{n-1} E(V_1^{(n-1)}) + E(V_1^{(n)}) + n \int_{\underline{v}}^{\bar{v}} ((1-F(y))^2 F^{n-2}(y)) dy
\end{aligned}$$

The expected revenue of the English auction is:

$$\begin{aligned}
ER^E &= (n-1)n \int_{\underline{v}}^{\bar{v}} \left( \frac{n-2}{n-1} \left( v - \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} \right) + \frac{\int_{\underline{v}}^{\bar{v}} x dF(x)}{1-F(v)} \right) F^{n-2}(v) (1-F(v)) f(v) dv \\
&= n(n-2) \int_{\underline{v}}^{\bar{v}} v F^{n-2}(v) f(v) dv - n(n-2) \int_{\underline{v}}^{\bar{v}} v F^{n-1}(v) f(v) dv \\
&\quad - (n-2)n \int_{\underline{v}}^{\bar{v}} \frac{\int_{\underline{v}}^v x dF(x)}{F(v)} F^{n-2}(v) (1-F(v)) f(v) dv \\
&\quad + (n-1)n \int_{\underline{v}}^{\bar{v}} \frac{\int_{\underline{v}}^{\bar{v}} x dF(x)}{1-F(v)} F^{n-2}(v) (1-F(v)) f(v) dv
\end{aligned}$$

$$\begin{aligned}
&= n \frac{n-2}{n-1} E \left( V_1^{(n-1)} \right) - (n-2) E \left( V_1^{(n)} \right) \\
&\quad - (n-2) n \int_{\underline{v}}^{\bar{v}} \int_{\underline{v}}^v x dF(x) F^{n-3}(v) (1-F(v)) f(v) dv \\
&\quad + (n-1) n \int_{\underline{v}}^{\bar{v}} \int_v^{\bar{v}} x dF(x) F^{n-2}(v) f(v) dv \\
&= n \frac{n-2}{n-1} E \left( V_1^{(n-1)} \right) - (n-2) E \left( V_1^{(n)} \right) \\
&\quad - (n-2) n \int_{\underline{v}}^{\bar{v}} \int_{\underline{v}}^{\bar{v}} 1_{x < v} x dF(x) F^{n-3}(v) (1-F(v)) f(v) dv \\
&\quad + (n-1) n \int_{\underline{v}}^{\bar{v}} \int_{\underline{v}}^{\bar{v}} 1_{x > v} x dF(x) F^{n-2}(v) f(v) dv \\
&= n \frac{n-2}{n-1} E \left( V_1^{(n-1)} \right) - (n-2) E \left( V_1^{(n)} \right) \\
&\quad - (n-2) n \int_{\underline{v}}^{\bar{v}} \int_x^{\bar{v}} F^{n-3}(v) (1-F(v)) f(v) dv x dF(x) \\
&\quad + n \int_{\underline{v}}^{\bar{v}} \int_{\underline{v}}^x dF^{n-1}(v) x dF(x),
\end{aligned}$$

such that

$$ER^E = -\frac{n}{n-1} E(V) + n E \left( V_1^{(n-1)} \right) - \frac{n^2 - 3n + 1}{n-1} E \left( V_1^{(n)} \right).$$

**Claim 15 (English and first-price auction revenue)** *In the D1 PBE  $ER^I > ER^E$ .*

**Proof.** We use that

$$E \left( V_2^{(n)} \right) = n E \left( V_1^{(n-1)} \right) - (n-1) E \left( V_1^{(n)} \right) \quad (22)$$

to write

$$ER^E = -\frac{n}{n-1} E(V) + E \left( V_2^{(n)} \right) + \frac{n}{n-1} E \left( V_1^{(n)} \right)$$

such that

$$\begin{aligned}
ER^I - ER^E &= -\frac{n}{(n-1)(n-2)} E(V) + \frac{1}{(n-1)(n-2)} E \left( V_1^{(n)} \right) + \frac{1}{n-2} E \left( V_2^{(n)} \right) \\
&= \frac{1}{(n-1)(n-2)} \left( -n E(V) + E \left( V_1^{(n)} \right) + (n-1) E \left( V_2^{(n)} \right) \right).
\end{aligned}$$



Note then that because

$$nE(V) = \sum_{k=1}^n E(V_k^{(n)}),$$

we have for  $n \geq 3$  (which is required for a D1 PBE)

$$ER^I - ER^E = \frac{1}{(n-1)(n-2)} \left( -\sum_{k=2}^n E(V_k^{(n)}) + (n-1)E(V_2^{(n)}) \right) > 0.$$

■

**Claim 16 (First- and second-price auction revenue)** *In the D1 PBE*  
 $ER^{II} > ER^I$ .

**Proof.** We use (22) to write

$$\begin{aligned} ER^{II} &= n \frac{n-2}{n-3} E(V_1^{(n-2)}) - nE(V_1^{(n-1)}) - \frac{n}{n-3} E(V) \\ &\quad + E(V_1^{(n)}) + n \int_{\underline{v}}^{\bar{v}} ((1-F(y))^2 F^{n-2}(y)) dy \end{aligned}$$

Then

$$\begin{aligned} ER^{II} - ER^I &= n \frac{n-2}{n-3} E(V_1^{(n-2)}) - nE(V_1^{(n-1)}) \\ &\quad - \frac{n}{n-3} E(V) + E(V_1^{(n)}) + n \int_{\underline{v}}^{\bar{v}} ((1-F(y))^2 F^{n-2}(y)) dy \\ &\quad - \left( -(n-1)E(V_1^{(n)}) + n \frac{n-1}{n-2} E(V_1^{(n-1)}) - \frac{n}{n-2} E(Y) \right) \\ &= n \left( E(V_1^{(n)}) - \frac{(n-2)+(n-1)}{n-2} E(V_1^{(n-1)}) + \frac{n-2}{n-3} E(V_1^{(n-2)}) \right) \\ &\quad - \frac{1}{(n-2)(n-3)} E(V) + \int_{\underline{v}}^{\bar{v}} ((1-F(y))^2 F^{n-2}(y)) dy \end{aligned}$$

Note then that

$$\begin{aligned} \int_{\underline{v}}^{\bar{v}} ((1-F(y))^2 F^{n-2}(y)) dy &= \int_{\underline{v}}^{\bar{v}} F^{n-2}(y) dy - 2 \int_{\underline{v}}^{\bar{v}} F^{n-1}(y) dy + \int_{\underline{v}}^{\bar{v}} F^n(y) dy \\ &= 2E(V_1^{(n-1)}) - E(V_1^{(n)}) - E(V_1^{(n-2)}), \end{aligned}$$

because by partial integration

$$\bar{v} = \int_{\underline{v}}^{\bar{v}} (yF^{n-2}(y))' dy = \int_{\underline{v}}^{\bar{v}} F^{n-2}(y) dy + \int_{\underline{v}}^{\bar{v}} y dF^{n-2}(y)$$

and the same for the other terms. Then

$$ER^{II} - ER^I = n \left( -\frac{1}{n-2} E \left( V_1^{(n-1)} \right) + \frac{1}{n-3} E \left( V_1^{(n-2)} \right) - \frac{1}{(n-2)(n-3)} E(Y) \right)$$

Then write

$$\begin{aligned} ER^{II} - ER^I &= n \int y \left( -\frac{n-1}{n-2} F^{n-2}(y) + \frac{n-2}{n-3} F^{n-3}(y) - \frac{1}{(n-2)(n-3)} \right) dF(y) \\ &= n \int y \left( -\frac{n-1}{n-2} u^{n-2} + \frac{n-2}{n-3} u^{n-3} - \frac{1}{(n-2)(n-3)} \right) dF(y) \end{aligned}$$

with  $u \equiv F(y)$  and define

$$G(u) = -\frac{n-1}{n-2} u^{n-2} + \frac{n-2}{n-3} u^{n-3} - \frac{1}{(n-2)(n-3)}.$$

Note then that

$$\int_0^1 G(u) du = -\frac{1}{n-2} + \frac{1}{n-3} - \frac{1}{(n-2)(n-3)} = 0$$

while  $G(0) = -\frac{1}{(n-2)(n-3)}$  and  $G(1) = 0$ . Moreover,

$$G'(u) = (-(n-1)u + (n-2)) u^{n-4} = 0$$

at  $u = \frac{n-2}{n-1}$ , a maximum since  $G''\left(\frac{n-2}{n-1}\right) = -(n-2)\left(\frac{n-2}{n-1}\right)^{n-4} < 0$ . Thus,  $G(u)$  must be strictly positive on an interval  $[0, u^*)$  and strictly negative on  $(u^*, 1)$ , while  $\int_{[0, u^*)} G(u) du = -\int_{(u^*, 1)} G(u) du$ .

Note then that  $y(u) = F^{-1}(u)$  is a strictly increasing function. Then by the intermediate value theorem we can find two values  $0 < y_1 < y_2$  such that

$$ER^I - ER^{II} = y_1 \int_{[0, u^*)} G(u) du + y_2 \int_{(u^*, 1)} G(u) du$$

while by the above

$$ER^I - ER^{II} = (y_2 - y_1) \int_{(u^*, 1)} G(u) du < 0.$$

■

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